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DUCTILE ALLOY ENCAPSULATED CERAMIC ARMOR DEVELOPMENT

January 1990

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ABSTRACT

The development of a fabrication process for encapsulating or cladding ballistic resistant ceramic materials with ductile metal alloys is described. Cladding is accomplished by powder metallurgy (P/M) technology in which an envelope of elemental metal powders, blended with elemental or master alloy powder additions, is cold isostatically pressed around the ceramic in an inexpensive, re-usable elastomeric mold. The P/M envelope is then further densified by vacuum sintering optionally followed by hot isostatic pressing (HIPing). The metal cladding can also be heat treated for further enhancement of its mechanical properties.

Besides the potential for improving ballistic armor performance, this P/M method of cladding offers wider flexibility in the design of ceramic armor systems allowing for the manufacture of multi-tile and multi-ceramic designs with the ceramic elements arranged and oriented in many different arrays. Furthermore, the metal cladding provides a means of attaching armor plates by welding, thus offering advantages in the repair and maintainability of armored vehicles.

The report describes the details of the optimized P/M cladding process of ceramics with titanium and aluminum base materials. Also described are efforts to evaluate and enhance the quality and strength of the bonding between the ceramics and the metal cladding.

Results of ballistic testing of different armor designs against .30 caliber and .50 caliber armor piercing threats are reported. The testing involved armor designs incorporating TiB_2 , Al_2O_3 and SiC ceramic tiles and clad either with titanium or aluminum alloy 6061 fabricated with and without the use of bonding aids and the optional HIP step. Also tested were multi-tile designs of TiB_2 clad with Ti-6Al-4V and Al_2O_3 clad with 6061 aluminum. In addition, preliminary armor designs incorporating ceramic particle reinforced metal matrix composites (microcomposites) of TiB_2 in Ti-6Al-4V and SiC in 6061 aluminum and clad with Ti-6Al-4V and 6061 aluminum, respectively, were tested.



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DUCTILE ALLOY ENCAPSULATED CERAMIC ARMOR DEVELOPMENT

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PROGRAM SUMMARY

This Small Business Innovation Research (SBIR) Phase II program has resulted in the development of a fabrication process for encapsulating ballistic resistant ceramic materials with ductile metal alloys. In its simplest embodiment monolithic tiles of ceramic armor materials (Al_2O_3 , TiB_2 , SiC , B_4C , etc) are clad on front and back faces and on all sides with either commercially pure aluminum or titanium or with structural alloys such as 6061 aluminum or Ti-6Al-4V.

The cladding process is accomplished by powder metallurgy (P/M) technology in which an envelope of elemental metal powders, blended with elemental or master alloy powder additions, is cold isostatically pressed around the ceramic in an inexpensive, re-usable elastomeric mold. The P/M envelope is then further densified by vacuum sintering optionally followed by hot isostatic pressing (HIPing). The metal cladding can also be heat treated for further enhancement of its mechanical properties.

Besides the potential for improving ballistic armor performance, this P/M method of cladding offers wider flexibility in the design of ceramic armor systems allowing for the manufacture of multi-tile and multi-ceramic designs with the ceramic elements arranged and oriented in many different arrays. Furthermore, the metal cladding provides a means of attaching armor plates by welding, thus offering advantages in the repair and maintainability of armored vehicles.

In the report which follows the details of the optimized P/M cladding process of ceramics with titanium and aluminum base materials are described. Also described are efforts to evaluate and enhance the quality and strength of the bonding between the ceramics and the metal cladding.

The majority of the report includes the results of ballistic testing of several different armor designs against .30 caliber and .50 caliber armor piercing threats. Included in the testing were armor designs incorporating TiB_2 , Al_2O_3 and SiC ceramic tiles and clad either with titanium or aluminum alloy 6061 fabricated with and without the use of bonding aids and the optional HIP step. Also tested were multi-tile designs of TiB_2 clad with Ti-6Al-4V and Al_2O_3 clad with 6061 aluminum. Finally, the results of testing preliminary designs incorporating ceramic particle reinforced metal matrix composites (microcomposites) of TiB_2 in Ti-6Al-4V and SiC in 6061 aluminum and clad with Ti-6Al-4V and 6061 aluminum, respectively is described.

The report concludes with a discussion of the potential applications of the clad armor technology developed in this SBIR program including suggestions for its further development.

INTRODUCTION AND REVIEW OF PROGRAM PLAN

In response to ever more lethal ballistic threats to military vehicles and personnel, considerable effort has been directed to the development of ceramic materials for armor systems. The high initial ballistic tolerance and light weight of ceramic materials are of great benefit. However, their inherent lack of toughness is a deficiency which limits their usefulness and deprives them of a much desired repeat-hit capability.

In a Phase I program Dynamet Technology successfully demonstrated a manufacturing feasibility to support and contain armor-quality ceramic tiles by cladding them with ductile metals and alloys applied by a proprietary advanced powder metal (P/M) process. However, the limited scope of this preliminary program did not allow for the development of an optimized cladding process. Thus, a complete assessment of the potential of the P/M cladding approach was not possible. Nevertheless, the results were encouraging and it was concluded that P/M ductile metal cladding if properly applied, might provide the support and containment needed to impart repeat-hit capability to ceramic armor materials. The key to achieving optimum support and containment, it was theorized, was to form a continuous strong and intimate bond between the metal cladding and the ceramic material. With good bonding the shock wave generated by ballistic impact could travel through the armor system without shattering the ceramic from the shock wave reflections.

In the preliminary work of the Phase I program some indications of strong bonding were observed with titanium powders fired on Al_2O_3 and TiB_2 ceramic tiles. Unfortunately, efforts to achieve strong bonding after sintering a fully encapsulated, full size ceramic tile were not completely successful. Subsequent hot isostatic pressing to bring the two materials into intimate contact and establish complete bonding achieved an opposite result. Additional shrinkage of the cladding during HIPing caused some of the clad materials to fail. Nevertheless, the results were encouraging enough to justify further development and a Phase II program was proposed to the Army and accepted.

The major objectives of the SBIR Phase II development program were to:

1. Refine and optimize the manufacturing steps of pressing, sintering and hot isostatic pressing for the various ceramic/metal cladding combinations of interest such that the following was achieved.
 - a. a strong ceramic-to-metal bond without cracking or other deterioration of the ceramic or metal cladding.

- 
- b. manufacturing flexibility for adjusting the relative thicknesses of cladding on armor front and back faces to obtain adequate support without excessive weight.
 - c. incorporate multiple ceramic elements in a cellular array with ductile metal separations and cladding.
2. Perform bonding studies of the various ceramic/metal cladding combinations of interest and explore methods of enhancing bonding by improved pre-processing of the ceramic surfaces and by the use of intermediate metallic films and layers as aids to bonding.
 3. Manufacture prototype armor plate designs and test them against typical ballistic threats to assess the effects of the modifications in the manufacturing procedures and the bonding enhancements and to compare the results to similar ceramic armor of conventional design.

The program was organized to be iterative in that ballistic test results of prototype targets would serve to guide further improvements in armor plate design and manufacture.

PROTOTYPE ARMOR PLATE FABRICATION

Manufacture of prototype armor plate designs for ballistic testing is based on Dynamet's powder metallurgy (P/M) technology in which complex shapes are formed by cold isostatic pressing (CIP) compactable metal powders in inexpensive, reusable elastomeric tooling. The CIPed preforms are then further consolidated by vacuum sintering at elevated temperature and fully densified by hot isostatic pressing (HIP) without the need for expensive enclosures or "cans" in order to accomplish densification.

The complete process known as the CHIP process (for Cold Hot Isostatic Pressing) has been successfully applied in a number of structural metal alloy systems including titanium and aluminum. CHIP processed materials can be manufactured to full (100% of theoretical) density with mechanical properties superior to castings and comparable to wrought products while providing the economic advantage of near-net shape fabrication.

Thus, the CHIP process is well suited for the powder metal encapsulation or cladding of light-weight armor quality ceramic tiles with the potential for developing impact resistance and an improvement in ballistic performance. Later in the program several metal alloy clad armor designs, utilizing a particle reinforced metal matrix composite core as the ballistic resistant element, were fabricated by a proprietary P/M CHIP processing method developed by Dynamet Technology. Some of the basic considerations and the techniques developed in this program to adapt the CHIP process to the cladding of ceramic armor systems are described in this section.

Tooling Design and Development

The basic tooling used to cold isostatic press (CIP) a metal encapsulated clad ceramic armor plate was an elastomeric mold with provisions for fixturing the ceramic tile core, and two steel plates for pressing the powder cladding material which fills the mold and surrounds the ceramic. Once filled, the mold with steel platens installed was closed, evacuated, vacuum sealed and isostatically pressed at pressures up to 55 ksi.

The initial experimental tooling used in the program was designed to establish the largest thickness and width dimensions of armor plates that could be conveniently CIPed in the available 8-inch diameter isostatic press¹. Once these maximum dimensions were established then various armor designs, using different types and sizes of ceramics and different thicknesses of cladding, could be fabricated.

¹The Dynamet press can accommodate plate lengths up to 20 inches and larger presses are available (with diameters up to 24 inches and lengths of several feet) when larger armor plates are needed.



For reasons of economy, in the initial experiments Al_2O_3 ceramic plates with dimensions 6 inch x 6 inch x 0.750 inch thick were used (Al_2O_3 plates are much less expensive than TiB_2 or SiC plates). Pre-cleaning consisted of an acetone wash, acid etching in Kroll's solution² and a hot water (150°F) rinse. The plates were then fixtured in the mold, encapsulated with commercial purity titanium (Ti) powder (-100 mesh) and CIPed at 55 ksi pressure. For the initial studies no interfacial bonding agent was used and the test plates were fabricated with equal cladding thicknesses on the front and back faces and along the edges.

The dimensions of the largest titanium clad Al_2O_3 experimental plate measured 8 inches wide x 1 5/16 inches thick. With the ceramic tile size used (6" x 6" x .75) this final plate size allowed total cladding thicknesses on the faces of up to 9/16 inch (9/32 on a side) and up to 1 inch on all sides.

Based on this result, modifications were made to the tooling to produce titanium clad (Al_2O_3) plates nominally 7 inches x 7 inches x 1 5/16 inches thick. The first plates which were pressed in the modified mold with flat sides were concave after CIPing. This was overcome by making a mold with convex sides. A further modification to the tooling was required to eliminate some slight edge cracking. The modification consisted of incorporating a radius on all corners of the powder clad plate.

The final tooling design for pressing armor plates for initial (baseline) ballistic testing is shown in Figure 1. This design provides final plate dimensions of 6 1/2 inches x 6 1/2 inches (nominal) with a total thickness up to 1 3/4 inches. It was used in fabricating initial baseline prototype ballistic test plates using both Al_2O_3 and TiB_2 ceramics, and its design features were incorporated in all modified tool designs for fabricating ballistic test plates of different sizes and compositions.

²An acid mixture, used for metallographic etching of titanium and titanium alloys, consisting of 10% hydrofluoric acid (HF), 5% nitric acid (HNO_3) and 85% water (H_2O).

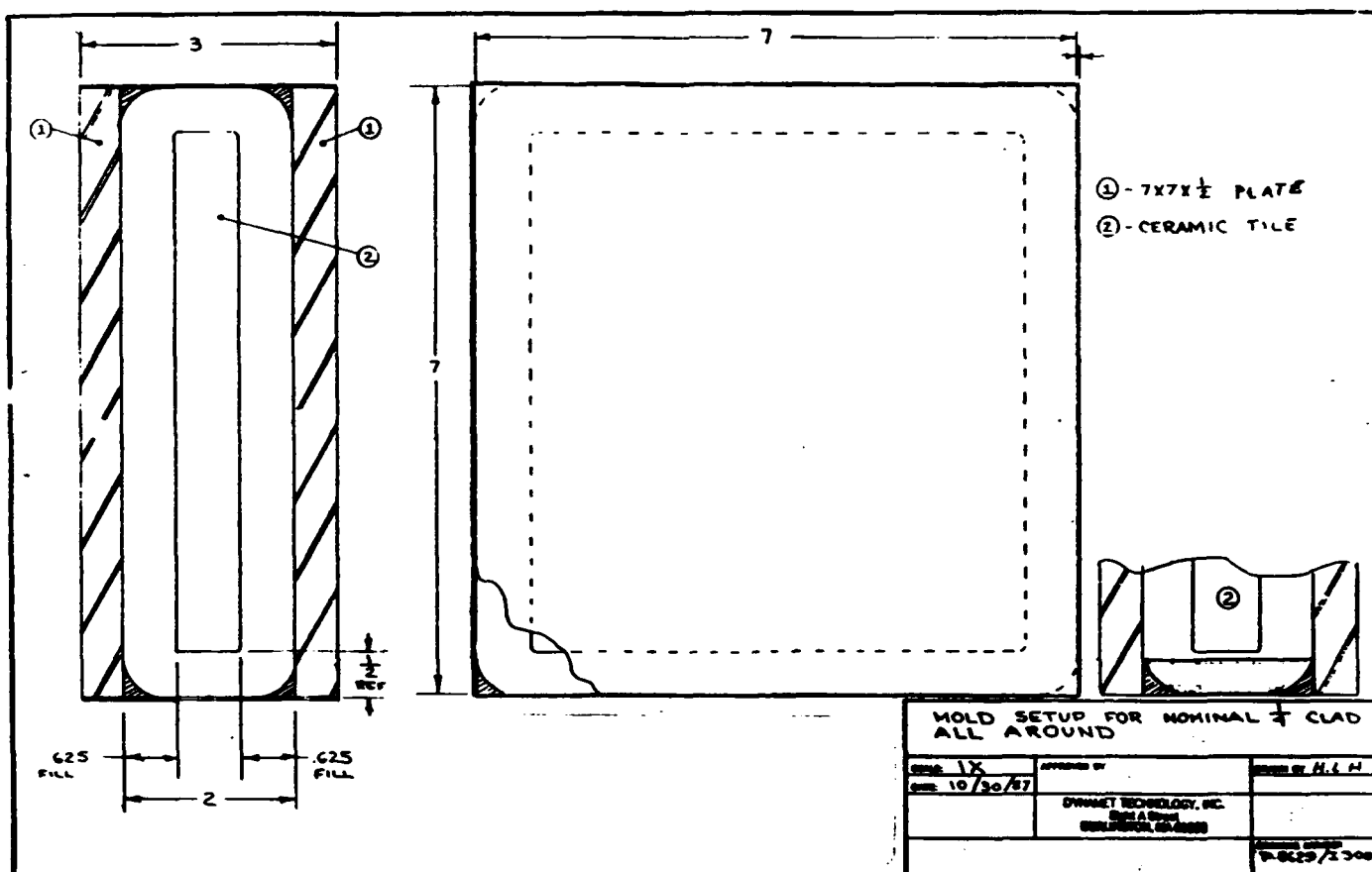


Figure 1. IMPROVED TOOLING DESIGN PROVIDING ROUNDED, CRACK-FREE CORNERS AND EDGES AND A UNIFORM THICKNESS OF CLADDING.

Cold Isostatic Pressing (CIP)

In the course of the program the cladding materials used included commercial purity titanium (as a cladding for both TiB_2 and Al_2O_3 ceramics), 6061 aluminum (for Al_2O_3 and SiC ceramics) and Ti-6Al-4V (for TiB_2 only). For the pure titanium or titanium alloy claddings the powder blend was loaded into the mold completely surrounding the ceramic and CIPed (after evacuating and sealing the mold) in a single step at 55 ksi.

For the ceramic plates clad with 6061 aluminum a two step CIP procedure was employed. The first step involved fixturing the ceramic plate in a mold in which the two faces of the ceramic were clad with the aluminum powder (about $\frac{1}{8}$ inch thick) and then CIPing at 20 ksi, as illustrated in Figure 2. The partially clad plate was then refixedtured into the original mold, surrounded by cladding material on all sides and repressed at 30 ksi, as illustrated in Figure 3, resulting in a uniform $\frac{1}{4}$ inch cladding thickness over the entire plate. All aluminum clad baseline armor designs were all manufactured by this two step procedure. Efforts to press aluminum cladding powder blends at the highest CIP pressure (55 ksi) resulted in cracking of the ceramic tiles in sintering whether the pressing was done in a one or two step process.

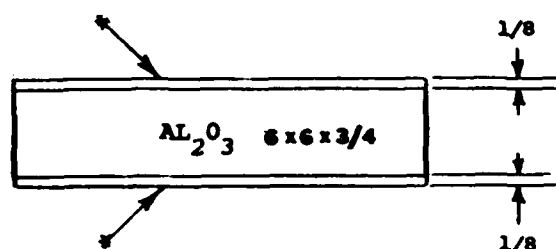
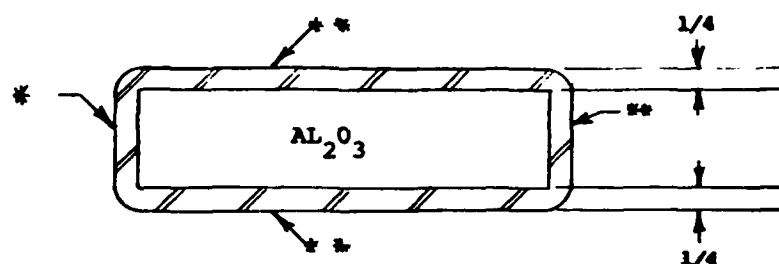


Figure 2. PARTIALLY CLAD CERAMIC RESULTING FROM THE FIRST PRESSING

Figure 3. FULLY ENCAPSULATED CERAMIC FOLLOWING THE SECOND PRESSING.



The density of the cladding material after CIP, whether aluminum or titanium based powder was used, was about 85% of full (theoretical) density.

Because the cladding on the armor front face (the face which is first to encounter the ballistic threat) contributes little to the ballistic performance compared to the cladding on the back face, an effort was made to fabricate an open-faced armor design using 6061 Al clad on the back face only of Al_2O_3 tiles. The sintering shrinkage of the pressed powder on the single clad face caused the armor plate to bend and resulted in cracking of both the cladding and the ceramic. Several changes in the manufacturing process were tried (reduced pressure in multi-step powder pressing) in an effort to eliminate the bending and cracking, but none were successful.

A modified process resulted in successful fabrication of armor designs with different cladding thicknesses in the front and back faces. To avoid cracking in sintering a symmetric clad layer of at least 1/8 inch on each face was pressed and sintered. This allowed a thicker cladding layer to be added (pressed and sintered) onto the original 1/8 inch thickness without cracking the ceramic tile.

Later in the program, in cladding multiple tile armor designs and armor designs based on cladding a metal matrix composite core (Dynamet's CM^3C technology), similar effects were encountered with non-symmetric cladding. In these instances, the problem manifested itself as bending of the armor plate, rather than cracking, due to the non-uniform sintering shrinkage. This problem was also overcome by pressing and sintering a symmetric cladding and then adding an additional clad layer to one face only.

Sintering

Sintering of clad ceramic plates was carried out as follows:

A. Titanium (pure or alloy) Cladding

Temperature = 2225°F

Time = 2 hours

Atmosphere = Vacuum of 10^{-5} Torr

B. Aluminum Alloy Cladding

Temperature = 1050°F

Time = 2 hours

Atmosphere = Nitrogen at reduced pressure
(50-200 microns)

In order to avoid cracking the ceramic tiles (Al_2O_3 , SiC or TiB_2) due to thermal shock, the heating and cooling rates had to be controlled at less than 125°F/hour; all sintering schedules adhered to this rule.

The clad plates were placed in the furnace on Al_2O_3 support discs and an Al_2O_3 plate was placed on top of the plate as shown in Figure 4. The latter plate was added to provide a uniform weight or force, to maintain contact between the ceramic and the cladding, and to enhance the tendency to form a ceramic-to-metal bond.

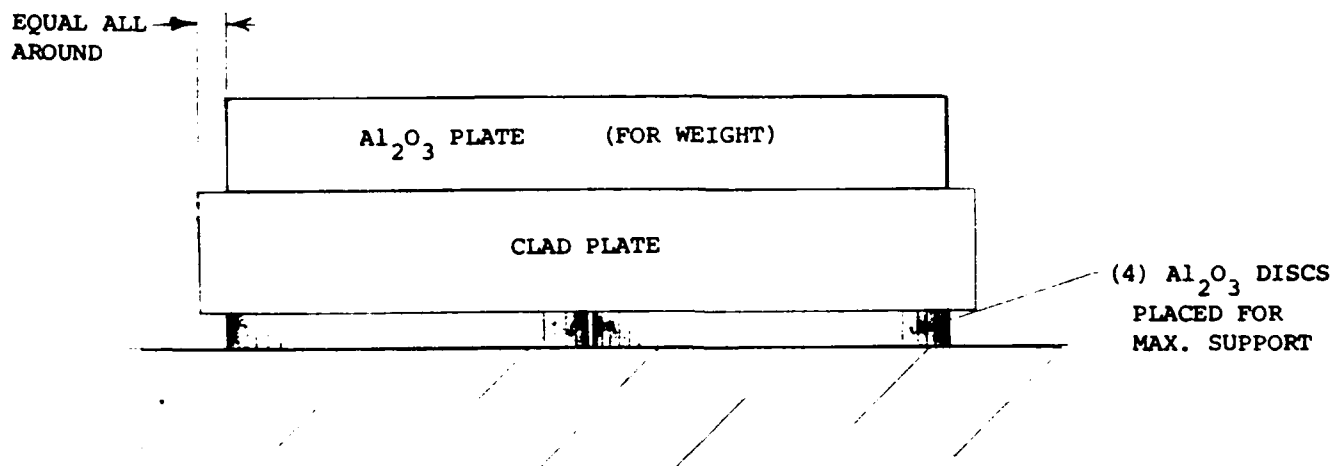


Figure 4. SINTERING FIXTURE



Hot Isostatic Pressing (HIP)

HIPing to fully densify the cladding was only used for selected ballistic test plates. When this operation was performed, the following processing conditions were followed:

Titanium Cladding (commercially pure or Ti-6Al-4V alloy)

Temperature	=	1650°F
Pressure	=	15,000 psi
Time	=	2 hours

Aluminum Cladding (alloy 6061)

Temperature	=	970°F
Pressure	=	15,000 psi
Time	=	2 hours

These HIP processing conditions were selected based on past experience with the cladding materials. They were followed in all cases whether the armor design incorporated a monolithic ceramic plate or a metal matrix microcomposite core (CM³C design).

CERAMIC-TO-METAL BONDING STUDIES

The initial metal cladding/ceramic armor tile combinations of interest included the following:

1. Titanium (pure) clad/TiB₂ ceramic
2. Titanium (pure) clad/Al₂O₃ ceramic
3. 6061 Aluminum clad/TiB₂ ceramic
4. 6061 Aluminum clad/Al₂O₃ ceramic

Later in the program the combination of 6061 aluminum clad/SiC ceramic was added.

To take full advantage of the metal encapsulation or cladding in the ballistic performance of clad ceramic armor designs, an intimate, continuous ceramic-to-metal bond is necessary. A variety of surface preparations and interfacial metallization techniques were evaluated with the three ceramic armor materials of interest (TiB₂, Al₂O₃, SiC). The methods that were evaluated and the results obtained are described in the following sections.

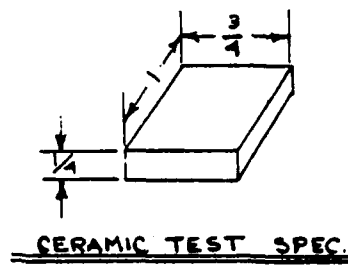
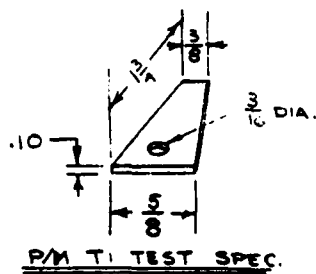
Surface Preparation - Pre-Cleaning

To obtain optimum metal-to-ceramic bonding, the first procedure to be established was that of cleaning the ceramic materials. The goal was to find a simple, effective cleaning method for the ceramic surfaces. Sample materials were cleaned by washing with acetone, alcohol, H₂O, trichlorethelene and Kroll's solution (titanium etchant), and by wire brushing. The cleaned ceramics were subsequently set on a small quantity of titanium powder (which had previously demonstrated some degree of self bonding in sintering), and vacuum sintered at 2200°F.

Upon examination of the sintered materials, it became apparent that although some bonding occurred under most cleaning conditions, the Kroll's solution cleaning produced the most substantial bond for both the Al₂O₃ and TiB₂ ceramics. It was also noted that the TiB₂ ceramic demonstrated a higher degree of bonding than the Al₂O₃ ceramic.

Bond Strength Testing

Quantitative values of metal to ceramic bond strength were determined by measurements of lap shear strength. To accomplish this measurement, small titanium segments were isostatically pressed from powder in a mold to produce small plates of 85% dense titanium. The titanium plates were then overlapped onto a ceramic segment, separated by a fine dispersion of the desired interfacial bonding alloy, as shown in Figure 5. The test samples were then sintered in a holding fixture, as illustrated in Figure 6. This fixture was designed to maintain intimate contact between the titanium plates and the ceramic material by applying a small force (weight) to each test sample. The assembly was vacuum sintered at 2200°F in order to bond the titanium segments to the ceramic plate. The bonded assembly was then tested in shear with the device illustrated in Figure 7.



TEST SPECIMEN ASSEMBLY

- BOND AREA

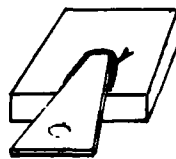


Figure 5. SKETCH ILLUSTRATING ASSEMBLY OF LAP SHEAR TEST SPECIMENS

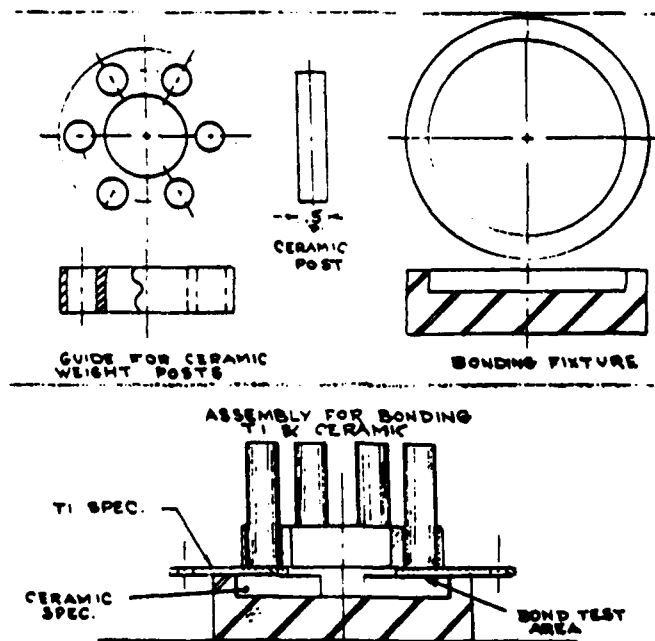


Figure 6. ILLUSTRATION OF ASSEMBLY FIXTURES FOR BONDING (SINTERING) LAP SHEAR TEST SPECIMENS.

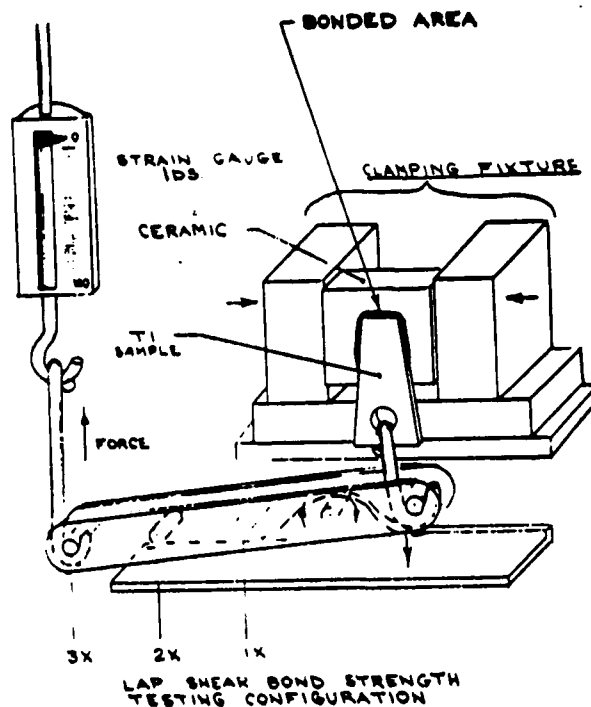


Figure 7. TEST FIXTURE FOR MEASURING LAP SHEAR STRENGTH OF BONDED CERAMIC-TO-METAL JOINTS.

The test fixture allows for application of forces from zero (0) to three hundred (300) pounds. By carefully measuring the bond surface area the bond strength is calculated in pounds per square inch (psi).

Titanium/TiB₂ Bonding

The initial work evaluated the bonding of a commercially pure titanium P/M cladding with both TiB₂ and Al₂O₃ ceramic tiles after sintering. The interfacial materials used in the initial evaluation were mixtures of titanium and iron (Ti and Fe) powders and included mixtures of 5%, 7%, 10%, 15% and 20% Fe with the balance being titanium.

A slightly different approach involved substituting nickel (Ni) powder for iron (Fe) and also applying pure Fe and pure Ni slurries to the ceramic faces. In this case, the ceramic faces carrying the "interfacial alloy" were bonded to pre-pressed titanium powder segments, which was more representative of the clad armor plate condition.

When sintered, all interfacial bonding agents, including the mixed combinations, demonstrated sound bonding on the TiB₂ ceramic, whereas only the 15% Ni, the 15% Fe and the pure Ni slurry bonded to the Al₂O₃ ceramic. Measured values of lap shear strength are shown in Table I. Successful bonding to TiB₂



Table I

LAP SHEAR STRENGTH OF TITANIUM BONDED TO CERAMICS
WITH VARIOUS INTERFACIAL BONDING AGENTS

Ceramic	Interface	Lap Shear Strength (psi)
TiB ₂	Ni Slurry	420
TiB ₂	Ni slurry	>760**
TiB ₂	85% Ni/15% Ti	>938**
TiB ₂	85% Ni/15% Ti	865
TiB ₂	15% Ni/85% Ti	740**
TiB ₂	10% Ni/90% Ti	557
TiB ₂	5% Ni/95% Ti	740
TiB ₂	5% Ni/95% Ti	>700**
TiB ₂	5% Ni/95% Ti	1281
TiB ₂	Fe Slurry	1019
TiB ₂	Fe slurry	1904
TiB ₂	Ni Slurry	>390**
TiB ₂	Ni Slurry	868
TiB ₂	15% Fe/85% Ti	120

**Failure load exceeded 300 pound maximum of test fixture

was also achieved with the other Fe-Ti mixtures, although shear strength measurements were not made. These results also demonstrated the relative ease of bonding titanium to TiB₂ and the general difficulty of bonding titanium to Al₂O₃.

Based on the results of the initial shear testing (Table I) three of the most promising interfacial material combinations for bonding Ti to TiB₂ were selected for more detailed testing. The three interface materials which imparted the best titanium to TiB₂ bonds were the 5% Ni-85% Ti slurry, the pure Ni slurry and the pure Fe Slurry.

Each interfacial slurry was formed by creating a suspension of the metal powder(s) in distilled H₂O. The slurry was applied to the acid etched ceramic material, the Ti segments placed on top of the slurry coating (as illustrated in Figure 5) and the material was vacuum sintered at 2200°F for 1/2 hour. The bond strength test results are shown in Table II.



TABLE II
Ti/TiB₂ Bond Strength Test Results

Interfacial Slurry	5% Ni/Ti	Ni	Fe
Lap Shear	740	420	1019
Bond Strength	700	762	1904
(pounds)	1281	498	0
	1824	741	0
	490	3213	
	85	2256	
	80	551	
		772	
Mean	743	1151	730
Standard Deviation	632	1018	917
Min.	80	420	0
Max.	1824	3213	1904

The nickel slurry coated TiB₂ samples demonstrated the highest average bond strengths, as well as the highest maximum and minimum values, compared to the other combinations. Of the three interfacial slurries tested, the nickel was also the easiest to apply. The iron slurry sometimes reacted with titanium during sintering and generated excessive heat, resulting in melting and no bonding at all. For these reasons, the nickel slurry became the preliminary choice for bonding titanium to TiB₂.

To further evaluate the Ti-Ni slurry/TiB₂ bond interface, a clad subsize armor plate was manufactured for metallographic sectioning and microlayer analysis. The subsize plate was produced using the production process established for fabricating full size Ti clad armor plates (described in the prior section of this report). Figure 8 shows a polished metallographic section at a corner of the clad TiB₂ ceramic. Four distinct zones or layers are evident including the following:

1. TiB₂ ceramic showing no indications of macro porosity, flaws or cracking.
2. Boron rich titanium intimately bonded to the TiB₂ ceramic with an approximate thickness of .004"
3. A nickel rich titanium region approximately .015 inch in depth.
4. An unaffected surrounding region of pure titanium.

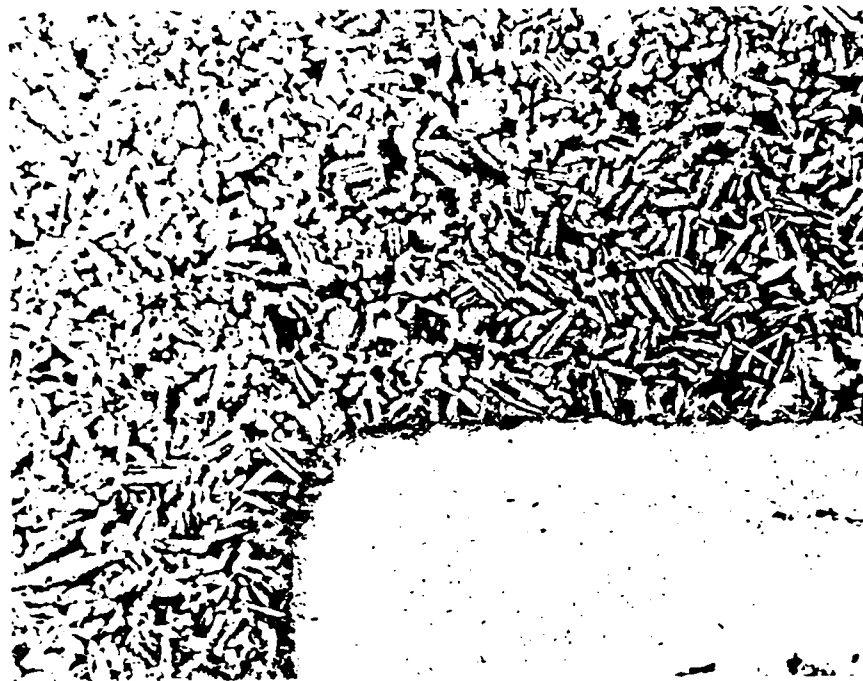


Figure 8. CORNER SECTION OF A SUBSIZE TITANIUM CLAD TiB₂ CERAMIC PLATE (100X).

From the higher magnification view of Figure 9, it appears that there is intimate bonding across the ceramic-metal interface with no apparent micro-cracks or separations (delamination). The intimate bonding was also confirmed by scanning electron microscopy (SEM) as shown in Figures 10-12. Figure 10 shows the region of the corner section that was examined, starting at the TiB₂ ceramic and progressing outward toward the unaffected titanium. Figures 11 and 12 present the more significant boundary layers, TiB₂ ceramic/boron rich titanium and the boron/nickel rich titanium regions, respectively.



Figure 9. INTERFACE OF TITANIUM CLAD (ABOVE) TiB_2 CERAMIC PLATE (BELOW) (500X)



Figure 10. CORNER SECTION OF THE TiB_2 /PURE TITANIUM CLAD PLATE AS SEEN BY SEM (100x).

Figure 12 clearly shows the irregular surface texture created by the bond interface advancing into the TiB_2 ceramic by the diffusion of titanium from the boron rich titanium. Also evident is the diffusion of boron into the titanium region, illustrated by the gray platelets mixed in with the needle-like structure on the titanium-rich side. This ease of diffusion during sintering is responsible for the consistent bonding obtained with the TiB_2 titanium system.

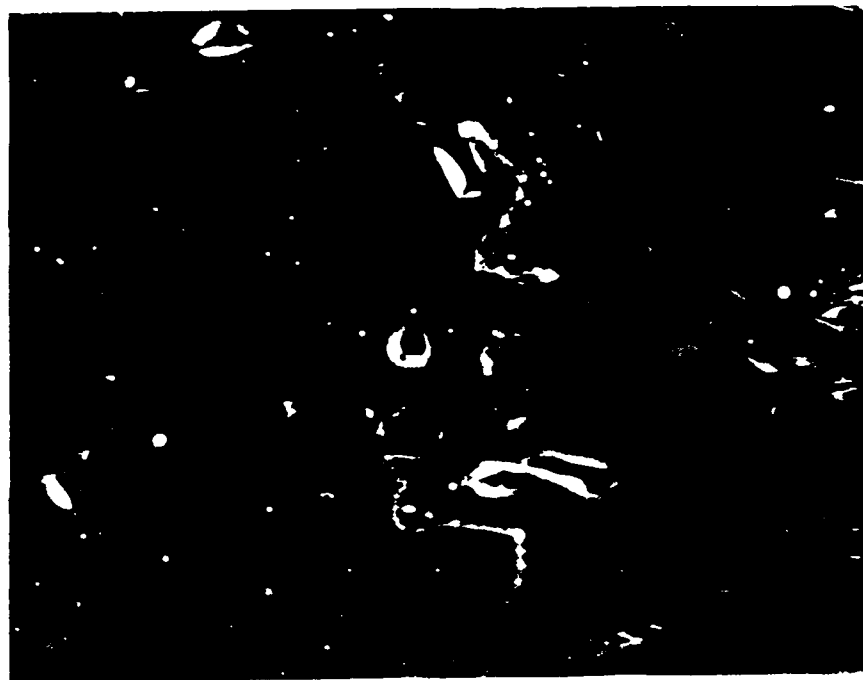


Figure 11. TiB_2 /BORON RICH TITANIUM INTERFACE (1000X). (Ceramic is at the left of the interface).

Figure 12 also shows the boundary layer where the boron rich titanium ends and the nickel rich titanium region begins. The elongated structure to the left is the edge of the boron rich area. To the right is the melted (eutectic) region created by the nickel slurry. The Ni-Ti eutectic areas are instrumental in creating the intimate bonding and demonstrate the need for and effectiveness of the nickel slurry in promoting bonding in this system. The eutectic layer formed by the nickel slurry is probably responsible for providing a path of easy diffusion for boron and titanium atoms across the metal-ceramic interface.

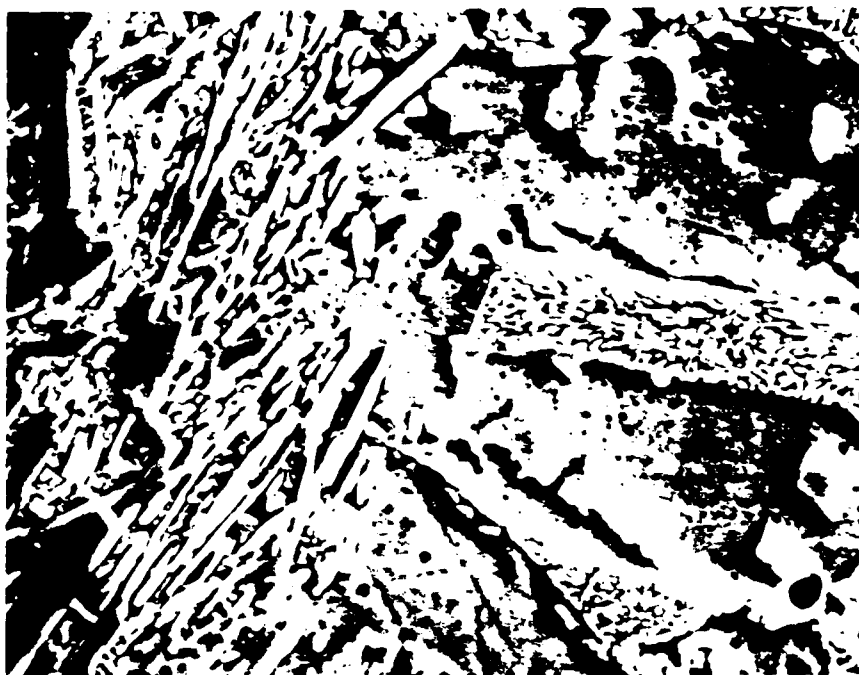


Figure 12. BORON RICH/NICKEL RICH TITANIUM INTERFACE (1000X).

Titanium/ Al_2O_3 Bonding

Attempts to attain intimate bonding of titanium to Al_2O_3 ceramics with the bonding aides used with TiB_2 had mixed success. For example, the nickel slurry, which demonstrated excellent performance with TiB_2 , would sometimes form a sound bond on Al_2O_3 and sometimes none at all.

Other interfacial bonding agents were studied in an effort to improve the $\text{Ti}/\text{Al}_2\text{O}_3$ bond strength. These included applying a "fired-on" nickel or Ni-Ti slurry alone or in combination with a thin metallization layer of either Mo-Mn or Mo-Mn-Ni alloy. The metallization process resulted in approximately a 10 layer of a Mo-Mn alloy deposited on the surface. An alloy paste is applied by a silk screening technique and was bonded to the Al_2O_3 by heating the material to approximately 2450°F. The metallization wets and bonds to the ceramic, allowing subsequent metal (clad) layers to bond not to Al_2O_3 , but to the thin metallization layer.

Other test samples received a similar treatment but with an extra layer of Ni (about 2 inches thick) applied over the Mo-Mn layer and fused in the same operation. It was speculated that the thin nickel coating might better bond to the Ti clad, as the studies with TiB_2 had shown. The limited test results of this bonding technique are given in Table II.

TABLE III
Ti/Al₂O₃ Bonding

Metallization Layer	Interfacial Slurry	Lap Shear Strength (pounds)
-	Ni	390
-	Ni	868
-	Ni	0
-	Ni	0
-	Ni	0
Mo-Mn	-	0
Mo-Mn	Ni	361
Mo-Mn-Ni	-	210
Mo-Mn-Ni	-	660
Mo-Mn-Ni	Ni	*
Mo-Mn-Ni	5%Ni/Ti	204

*Sample fused to fixture, fractured ceramic, bond intact

Despite the small number of samples and the inconsistent results, this approach appeared to be worth developing. Microlayer studies indicated the possibility of strong bonding. As illustrated in Figure 13, the results were similar to those obtained with TiB₂. The bond interface consisted of several distinct regions or layers. The dark region at the bottom represents the Al₂O₃ ceramic, with some inherent microporosity, but with no indications of cracks or voids. The light layer directly above is the .0007 inch thick Mo-Mn-Ni metallization in contact with the Al₂O₃ ceramic, as well as the next distinct layer of eutectic nickel-titanium, (.0014 inch thick), resulting from the reaction of titanium with the nickel slurry. Approximately .0045 inch above the Al₂O₃ is a continuous region of unaffected titanium. There is no evidence of delamination, macro porosity in the clad titanium or cracks or voids within the ceramic. As in the case of titanium clad TiB₂ the irregular texture at the interface in Figure 13 is an indication of diffusional bonding of the cladding to the metallized ceramic.

Despite the apparent success of this bonding approach, the ballistic performance of prototype titanium clad Al₂O₃ ceramic plates was not satisfactory (see next section on ballistic testing). For this reason the effort to clad Al₂O₃ with pure titanium was abandoned in favor of cladding Al₂O₃ with 6061 Al.

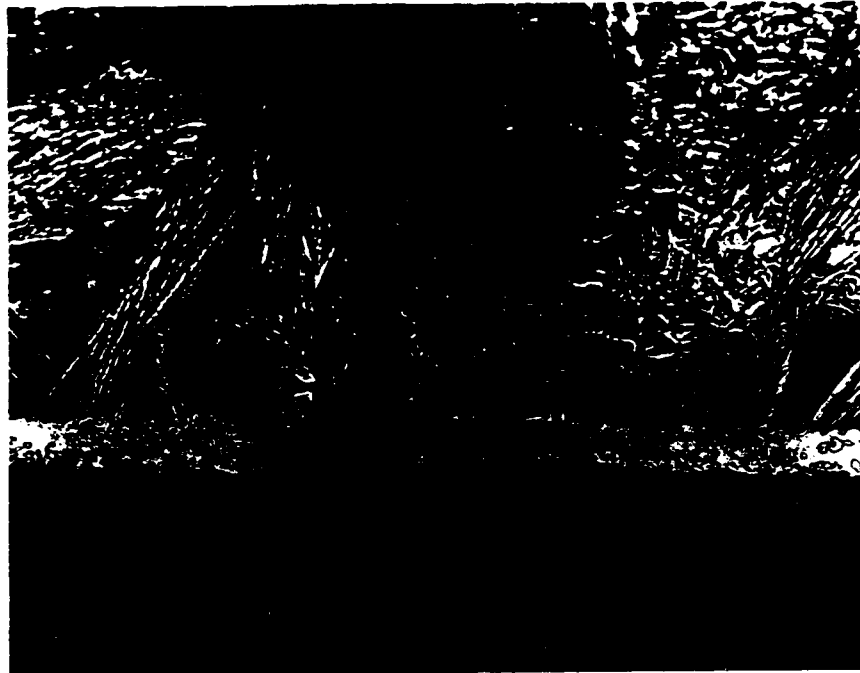


Figure 13. SEM VIEW OF CROSS SECTION OF THE PURE TITANIUM CLAD METALLIZED (Mo-Mn-Ni) Al_2O_3 CERAMIC BONDED WITH A BONDING AIDE (500X).

6061 Aluminum/Ceramic Bonding

The bonding the P/M 6061 aluminum (Al) alloy cladding to the two ceramics of interest is inherently more difficult than bonding the P/M titanium cladding. The sintering temperature of titanium (2200°F) is high enough to allow for the reactions of metal to ceramic, which enhance bonding, to take place. Aluminum alloys, however, are sintered in a much lower temperature range (1050°F - 1125°F), thus limiting the types of reactions which can occur. This limitation, combined with the tenacious oxide which forms on aluminum, are a deterrent to effective ceramic-to-metal bonding.

Initially attempts were made with untreated Al_2O_3 and with various low melting point lead/tin alloys. These efforts were unsuccessful. In addition, two commercial products for bonding metallic (aluminum) and ceramic materials were tried. The first, CUSIL-ABA (a product of Wesgo division of GTE) is a .002 inch foil which was vacuum fired at 1550°F directly on to the surface of TiB_2 and Al_2O_3 plate samples prior to metal cladding and sintering. The second involved a brazing paste, Alumibraz 400, which was applied to both ceramics as a slurry prior to metal cladding. Neither approach provided consistent bonding of the 6061 Al cladding to either of the ceramics.

Various metallization procedures were then evaluated. Sub-size plates of Al_2O_3 ceramic were metallized with a 0.0009 inch thick layer of Mo-Ni-Cu, with the outer copper layer being 0.0005 inch thick. As with full-size ballistic test plates, the sub-size ceramic plates were then clad with 6061 Al by isostatic powder compaction and sintering. To evaluate the interfacial bonding with and without metallization in a single metallographic cross-section, only one surface of the ceramic was metallized prior to applying the aluminum cladding to both sides of the ceramic.

Figure 14 is an unetched photomicrograph of a corner section of a Mo-Ni-Cu metallized sub-size Al_2O_3 ceramic plate clad with 6061 Al. The large dark area is the ceramic which appears to be free of microcracks and porosity. The lighter area which surrounds the ceramic is the 6061 Al cladding. Along the non-metallized ceramic/clad interface a distinct boundary is evident, but there are no indications of separation or delamination between the two regions.

At the metallized interface molybdenum has diffused into the ceramic as indicated by the light region within the ceramic. As a result, the original interface between ceramic and metallization has been eliminated and the ceramic and metallization are chemically bonded. Also evident in Figure 14 are the copper layer (0.0005 inch thick) in contact with the aluminum/cladding and an intermediate nickel layer separating the copper and molybdenum layers.

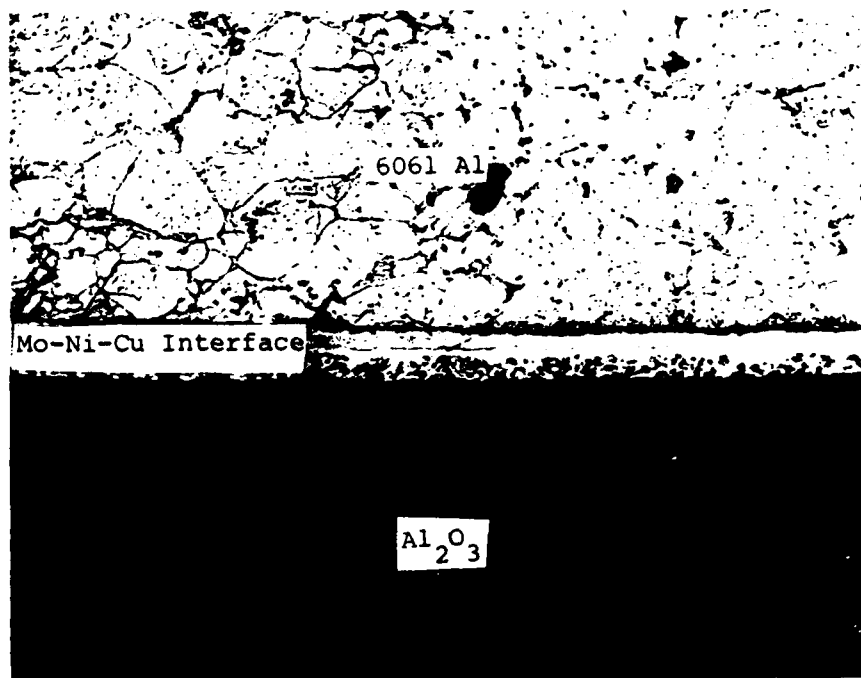


Figure 14. CROSS-SECTION OF METALLIZED Al_2O_3 /6061 Al SUB-SIZE TEST PLATE. LIGHT AREA (ABOVE AND TO LEFT) IS 6061 Al AND DARK AREA IS Al_2O_3 . NOTE Mo-Ni-Cu METALLIZATION (HORIZONTAL LAYER) WITH CONSTITUENTS LABELED AND NON-METALLIZED INTERFACIAL BOUNDARY AT LEFT (200X).

As with the metallized Mo-ceramic interface, the metallized Cu layer and the 6061 Al cladding appear to be chemically bonded with no indications of cracking, delamination or separation between the individual layers.

A second bonding system based on a Mo-Mn metallization was also evaluated on sub-size Al_2O_3 ceramic tiles clad with 6061 Al. The Mo-Mn metallization exhibited similar bonding properties as the Mo-Ni-Cu metallization. As a result prototype armor plates were manufactured for ballistic testing using both types of metallization to determine which metallization system would give the better ballistic performance compared to non-metallized Al_2O_3 /6061 Al armor design.

No further efforts were made to bond 6061 Al to the TiB_2 ceramic. However, later in the program SiC ceramic was added as a candidate ceramic armor for ductile metal encapsulation with 6061 Al.

To enhance the bonding between the SiC ceramic and the aluminum alloy cladding both the Mo-Ni-Cu and Mo-Mn metallizations were tried with SiC sub-size tiles. Both metallizations exhibited poor adherence to the ceramic. Successful adherence to SiC was obtained with a silver (Ag) metallization and SiC test tiles with Ag metallization were clad with 6061 aluminum for metallographic evaluation of the ceramic/clad bonding. These micro-layer studies indicated sound and consistent bonding of clad to ceramic, and prototype SiC/6061 Al clad armor plates were manufactured for ballistic testing.

BALLISTIC TESTING OF PROTOTYPE ARMOR DESIGNS

Ballistic testing was performed by MTL at their ballistic laboratory in Watertown, Massachusetts. Armor piercing (APM2) threats of both .30-caliber and .50-caliber were employed. The scope of the testing including the selection of test conditions (threat velocity, back-up support, etc.) was performed by MTL personnel and supervised by Stephen Mariano. The following sections describe the prototype armor designs tested and summarize the ballistic test results.

Baseline Armor Designs

The baseline armor test plates were based on a cladding of commercially pure titanium (Ti) on tiles of Al_2O_3 ceramic (A-T series) and TiB_2 ceramic (T-T series). A variation of these series consisted of a nickel metallization on the ceramic plates (designated NS for the nickel slurry) which was applied to the ceramics and fired-on to enhance bonding between the ceramic and the cladding. The final series of baseline plate designs consisted of Al_2O_3 ceramic tiles clad with 6061 Al (A-A series).

The ceramic tiles used for these series were 6 inch squares x 0.750 inch in thickness. The baseline armor plates with powder metal cladding measured about 6 1/2 inches x 6 1/2 inches x 1 5/16 inches after sintering with 1/4 inch of cladding on all edges and an equal cladding thickness on each face of about 9/32 inch. Cladding density was approximately 95% of theoretical density. Baseline plates of the A-T, T-T and the A-A series after sintering are shown in Figures 15 and 16.

These baseline armor designs were all tested against a .50-caliber AP M2 threat at strike velocities just below 3000 ft/sec. For the ballistic testing, all target plates (except as noted) were rigidly clamped to a 0.500-inch thick aluminum (alloy 7039) back-up plate. Most of the target plates were tested as sintered, but examples of A-T and T-T plates were HIPed to further densify the cladding and (possibly) to enhance the bonding between ceramic and cladding.

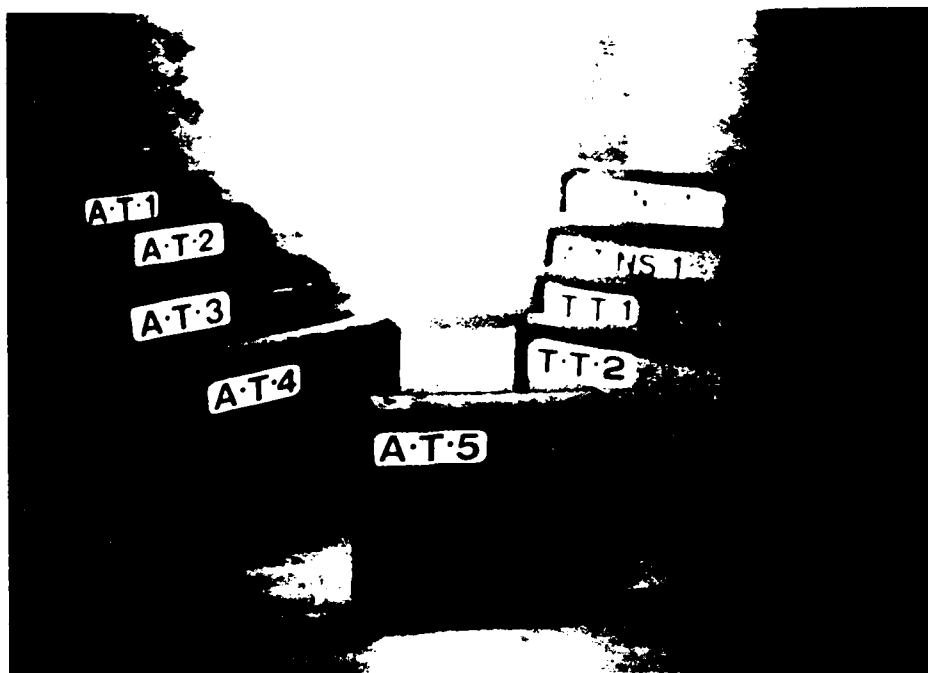


Figure 15. BASELINE ARMOR PLATE DESIGNS EMPLOYING COMMERCIALY PURE TITANIUM CLADDING ON Al_2O_3 CERAMIC (A-T SERIES) AND ON TiB_2 CERAMIC (T-T SERIES).



FIGURE 16. BASELINE ARMOR PLATE DESIGNS EMPLOYING 6061 ALUMINUM ALLOY CLADDING ON Al_2O_3 CERAMIC PLATES (A-A SERIES).



A summary of the ballistic testing of the baseline armor designs is provided by Table IV. All of the TiB_2 clad plates displayed satisfactory ballistic performance. Views of these plates after testing are presented in Figures 17-19. The test results do not indicate a measurable improvement in ballistic performance due to the nickel metallization (plate T-T-NS-1) or the addition of the HIP step (plate T-T-1). In all cases the test plates successfully defeated the threat with damage to the plates consisting of severe entrance hole petaling (Figure 18A) and backside bulging (Figure 19).

Table IV.

BASELINE ARMOR DESIGNS AND BALLISTIC TEST RESULTS AGAINST A .50 - CALIBER APM2 THREAT

Test Plate Identification	Cladding Material	Bonding Agent	Process	Backup Support	Total		Threat Velocity ft/sec	Observations
					Areal Density (psf)			
T-T-2	Ti	None	CIP/Sinter	0.5inch Al	36		2959	Partial penetration/No cracking/ Entrance hole petaling
T-T-NS-1	Ti	Ni Slurry	CIP/Sinter	0.5inch Al	36		2977	Partial penetration/No cracking/ entrance hole petaling
T-T-1	Ti	None	CHIP	0.5inch Al	36		2921	Partial penetration/No cracking/ entrance hole petaling
A-T-2	Ti	None	CIP/Sinter	None	25		2933	Complete penetration
A-T-3	Ti	None	CIP/Sinter	0.5inch Al	32		2998	Partial penetration cracking- front and rear faces
A-T-5	Ti	None	CIP/Sinter	0.5inch Al	32		2940	Partial penetration cracking- front and rear faces
A-T-NS-1	Ti	Ni Slurry	CIP/Sinter	0.5inch Al	32		2951	Partial penetration cracking- front and rear faces
A-T-1	Ti	None	CHIP	0.5inch Al	32		2814	Partial penetration cracking- front and rear faces
A-T-4	Ti	None	CHIP	0.5inch Al	32		2966	Partial penetration cracking- front and rear faces
A-A-6	6061 Al	None	CIP/Sinter	0.5inch Al	32		2993	Partial penetration cracking- rear face
A-A-7	6061 Al	None	CIP/Sinter	0.5inch Al	29		2975	Partial penetration cracking rear face



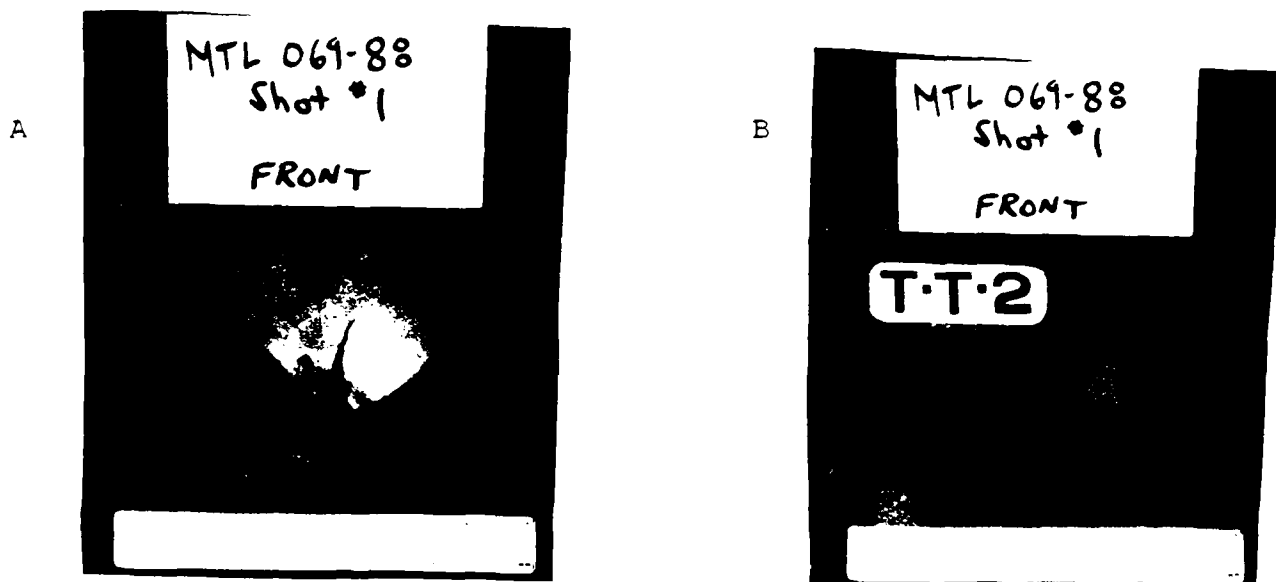


FIGURE 17. TiB_2 CLAD BASELINE ARMOR DESIGN TESTED IN AS-SINTERED CONDITION SHOWING DAMAGE TO FRONT FACE (A) AND BACK FACE (B).

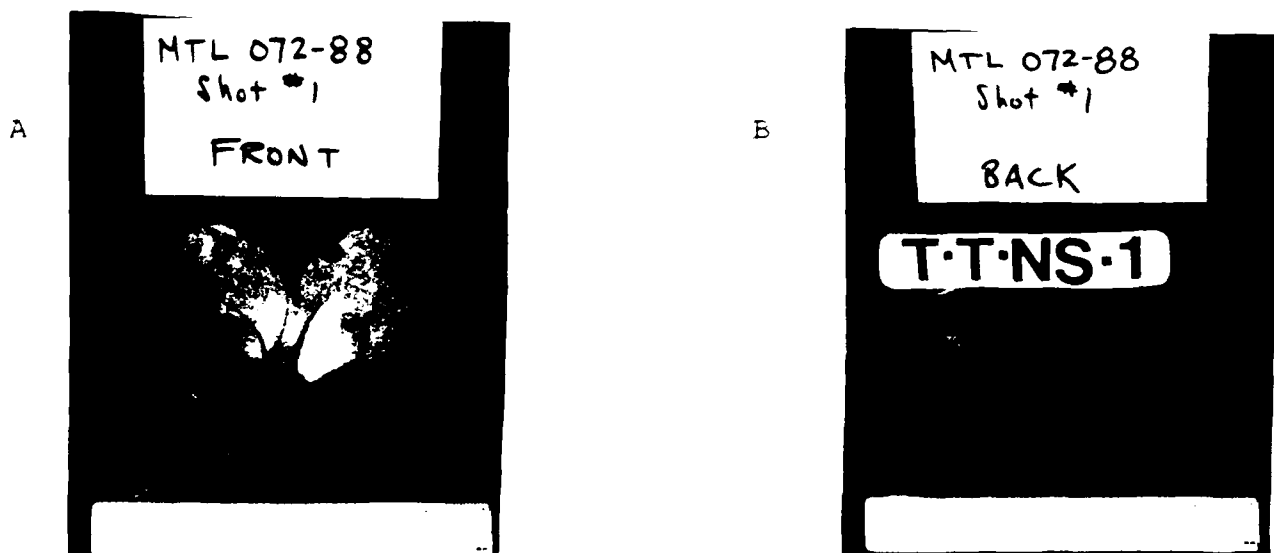


FIGURE 18. TiB_2 CLAD BASELINE ARMOR DESIGN WITH NICKEL METALLIZATION TESTED IN AS-SINTERED CONDITION SHOWING DAMAGE TO FRONT FACE (A) AND BACK FACE (B).

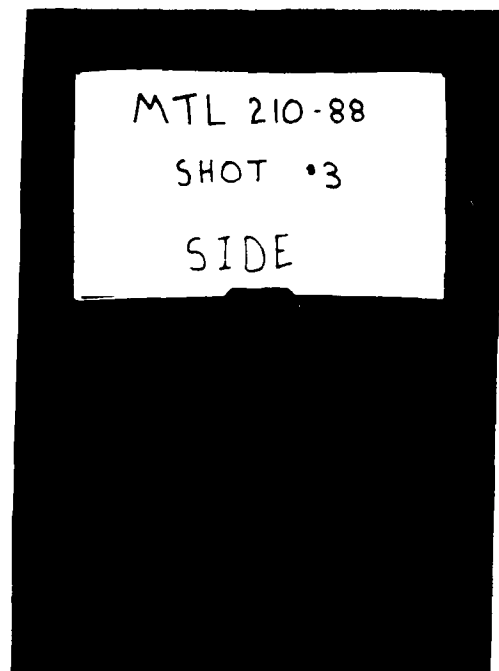


FIGURE 19. SIDE VIEW OF TiB_2 CLAD BASELINE ARMOR DESIGN TESTED IN HIPed CONDITION SHOWING LIMITED BULGING TO BACK FACE (AT RIGHT)

Observations of the Ti-clad Al_2O_3 targets indicated that cracking of the cladding was a severe problem when tested against the 50-caliber threat (Table IV). This was observed in all of the as-sintered plates including the one with a nickel metallization (A-T-NS-1). Furthermore, the plates that were HIPed did not show any significant improvement over the sintered plates. The typical damage consisted of cracking of both front and back faces and a prominent bulge on the back face as shown in the profile views of plates A-T-1 and A-T-4 in Figure 20.

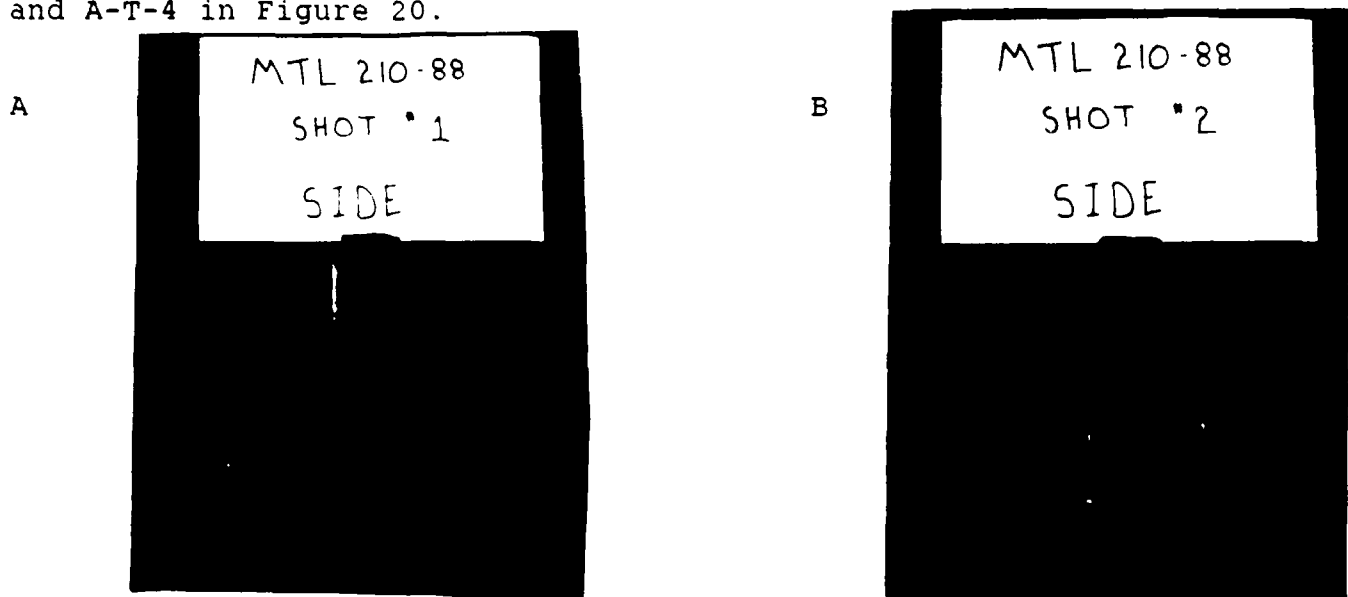


FIGURE 20. SIDE VIEWS OF HIPed TITANIUM-CLAD Al_2O_3 ARMOR PLATES A-T-1 (A) AND A-T-4 (B). NOTE CRACKING AND BULGING OF THE BACKSIDES (AT LEFT).

With regard to the penetration resistance of the targets, all armor materials systems performed equivalently except target A-T-2 which was unsupported by a 0.5 inch 7039 aluminum backup plate. This proved that the cladding did not have sufficient strength to support the ceramic tile. This lead to premature tensile failure of the ceramic and consequently low ballistic limits.

The nickel slurry bonding aide applied to the TiB_2 and Al_2O_3 ceramic tiles had no measurable effect on the penetration resistance and the multiple-hit properties of the armor systems tested. Furthermore, the subsequent HIP step appeared to be ineffective in improving the multi-hit performance. The minor increase in strength and density of the cladding was insufficient to effect the ballistic performance of these systems. It is also logical to conclude that the minor strength improvement of a fully dense cladding would not be sufficient to support the ceramic properly thus making the ceramic/clad armor system ineffective as a stand alone armor (i.e., with no aluminum backup plate).

From the ballistic results and observations after impact it was evident that the TiB_2 ceramic clad with titanium offered the best opportunity for a multi-hit armor system. The TiB_2 with titanium cladding exhibited no excessive cracking in the cladding and did exhibit petaling around the entrance hole. The latter observation provides evidence of ductile failure in the clad.

Although the targets with Al_2O_3 ceramic with 6061 displayed cracks on the rear surface after ballistic impact, the cracks were not excessive, thus justifying further evaluation of this design as potential multiple-hit armor system. The targets of Al_2O_3 clad with titanium exhibited major cracks on both the front and rear surfaces and thus would not be a suitable candidate armor system against multiple impacts. Based on this result, it was decided to focus attention on 6061 Al cladding on Al_2O_3 ceramic tiles and to eliminate titanium clad Al_2O_3 plates from further development studies.

Al_2O_3 /6061 Armor Designs - Comparative Ballistic Performance

This test series was conducted to compare the ballistic performance of 6061 clad Al_2O_3 armor systems with conventional steel and ceramic armor systems. Three target designs were fabricated specifically to be compared to conventional Al_2O_3 aluminum backed armor systems. The specific armor designs were taken from MTL TR 81-20 (1981), "Ballistic Technology of Light Weight Armors" by F. Mascianica. Table V describes the armor designs for this test series.



Table V

P/M FABRICATED 6061 ALUMINUM CLAD/ Al_2O_3 CERAMIC ARMOR DESIGNS

Test Group	Ceramic Thickness Inches	Clad Thickness*	Total Thickness Inches	Areal Density (psf)
1	0.340	0.20 inch/side	0.740	11.9
2	0.340	0.25 inch/side	0.840	13.6
3	0.600	0.425 inch front 0.20 inch back	1.225	19.9

*Dimensions are approximate within ± 0.025 inch.

Group #1 and #2 targets were designed to be tested against .30 caliber APM2 threats while targets of Group #3 were to be tested against .50-caliber APM2 threats. All target plates were fabricated with 6 1/2 inch x 6 1/2 inch areal dimensions and incorporated Al_2O_3 ceramic tiles measuring 6 inches x 6 inches.

The pressing pressure used in cladding (isopressing) the initial Al_2O_3 /6061 Al clad plates with aluminum alloy powder was 55,000 psi. However, in the interfacial bonding studies, some surface microcracking of the Al_2O_3 ceramic was observed after pressing at this pressure. As a result the pressure used in manufacturing the ballistic test plates of Table V was reduced to 25,000 psi. The result was a reduction in density after sintering of the 6061 Al cladding from about 96% to about 94% of theoretical density.

By eliminating microcracking in the Al_2O_3 ceramic it was hoped that the ballistic performance would be improved despite the expected compromise in the mechanical properties resulting from the reduced density. To test the effect of clad density, two plates in the Group #1 with 0.20-inch thick cladding were HIPed to increase the density of the cladding to about 98% of theoretical.

The Group 3 targets were fabricated by the same methods as described for the 30-caliber threat targets. The design consisted of a 0.600 inch thick Al_2O_3 tile (6-inch x 6-inch) clad on the back face with 0.425 inch thick 6061 Al cladding and on the front face with 0.200-inch thick 6061 Al cladding. Originally, a design without any front face cladding was attempted. However, to prevent excessive distortion and cracking during sintering, it was necessary to clad the front face with a thinner layer of 6061 Al.

Six full size (6 1/2 x 6 1/2) prototype targets of this design were manufactured and tested against a 50-caliber AP threat. These plates were tested in the as-sintered condition. The ballistic performance of all the test plates under the selected test conditions is summarized in Table VI.



The three plates with 0.250 inch clad thickness (Group #2) were tested without backup support plates at threat velocities of 3205 ft/sec, 2812 ft/sec and 2342 ft/sec. These three tests resulted in three complete plate penetrations leaving an approximate 2 inch diameter void on the back side of the plate (Figure 21). The ceramic in the immediate vicinity of the passageway of the 30-caliber threat was broken down into small fragments and powder size particles, while the ceramic outside the immediate strike vicinity suffered radial cracking and chipping. The cladding on the back surface tended to peel away around the strike zone leaving a 2 inch diameter hole. However, no delamination, bulging or cracking was observed outside the immediate strike zone.

A second group of three tests was conducted with the plates with 0.25 inch thickness of cladding and with the addition of an 0.25 inch thick aluminum (alloy 7039) backup plate to provide extra support. Threat velocities were similar to those of the test, with the support plate added. As expected, the damage to the back side of the test plate was considerably less than that of the unsupported plates. A small bulge protruding approximately 1/2-inch beyond the back surface was typical of all three plates (Figure 22). Minor cracking was found in the vicinity of the bulge, resulting in an area where a small amount of ceramic was either exposed or left unsupported by the cladding material. As with the non-supported plates, no cracking, delamination or bulging was evident outside the initial strike zone.

Table VI

BALLISTIC PERFORMANCE OF $Al_2O_3/6061$ CLAD ARMOR DESIGNS FOR COMPARISON TO CONVENTIONAL ARMOR DESIGNS

Group No.	Test No. (Threat)	Shot No.	7039 Aluminum		Total Areal Density (psf)	Impact Velocity (ft/sec)	V ₅₀ (ft/sec)	Results
			Backup	Added				
1	88-256 (.30 APM2)	1	0.250	inch	15.5	2XXX**		Partial Penetration
		2	0.250	inch	15.5	2XXX**		Partial Penetration
		3	0.250	inch	15.5	2XXX**		Complete Penetration
		4	0.250	inch	15.5	2XXX**	2XXX**	Complete Penetration
1*	88-517 (.30 APM2)	1	0.250	inch	15.5			
		2	0.250	inch	15.5		2XXX**	
2	88-254 (.30 APM2)	1	None		13.6	3205		Complete Penetration
		2	None		13.6	2812		Complete Penetration
		3	None		13.6	2342		Complete Penetration
		4	0.250	inch	17.1	2801	2XXX**	Partial Penetration
		5	0.250	inch	17.1			
		6	0.250	inch	17.1			
3	88-288 (.50 APM2)	1	None		19.9	2740		Complete Penetration
		2	0.125	inch	21.7	2762		Complete Penetration
		4	0.250	inch	23.4		2XXX**	
		5	0.250	inch	23.4			

*Targets were HIPed after sintering

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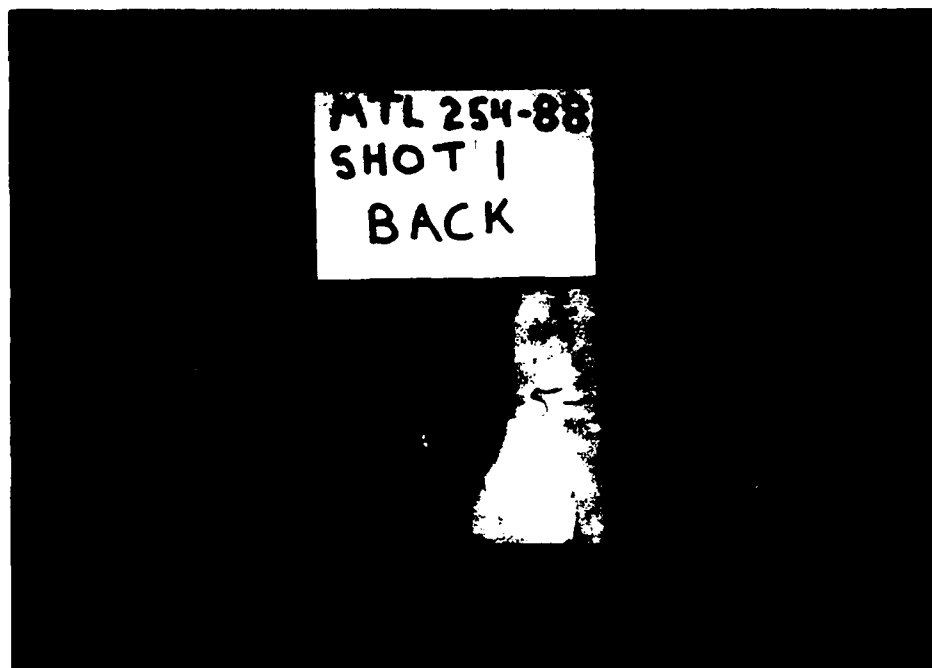


Figure 21. VIEW OF BACK FACE OF Al_2O_3 /6061 AL CLAD BALLISTIC TEST PLATE. PLATE CONSISTED OF 0.34 INCH THICK Al_2O_3 TILE CLAD ON BOTH FACES WITH 0.25 INCH OF 6061 AL. TEST WAS PERFORMED WITHOUT A BACKUP PLATE.

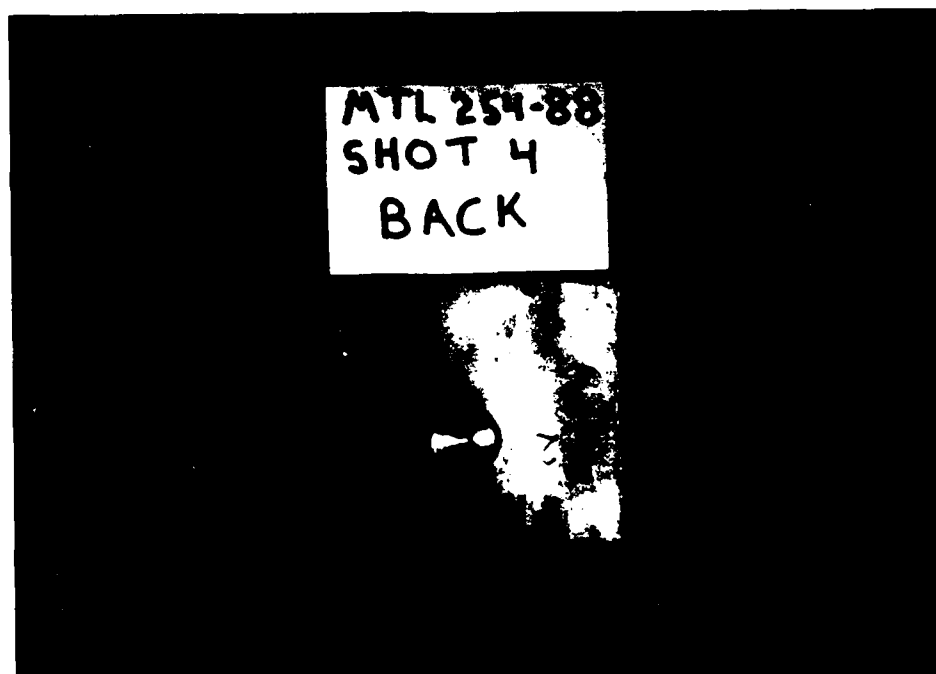


Figure 22. VIEW OF BACK FACE OF Al_2O_3 /6061 AL BALLISTIC TEST PLATE. ARMOR CONFIGURATION WAS THE SAME AS IN FIGURE 21 BUT TEST PLATE WAS SUPPORTED WITH 0.250 INCH ALUMINUM BACKUP PLATE.

The four test plates in Group #1 with the reduced cladding thickness were tested with a supporting (7039 aluminum alloy) backup plate. The ballistic performance was comparable to that of Group #2 of (supported) targets. The damage consisted of moderate bulging on the backside with minimal cracking at the point of impact and no damage outside the initial strike zone (Figure 23).

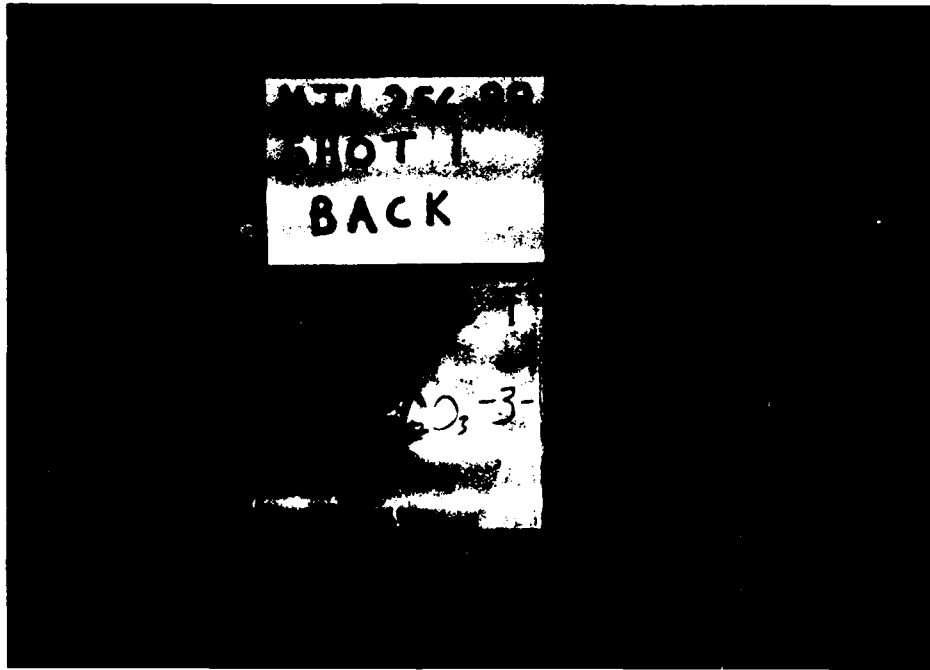


Figure 23. VIEW OF BACK FACE OF Al_2O_3 /6061 AL BALLISTIC TEST PLATE. ARMOR CONFIGURATION WAS SIMILAR TO FIGURES 21 AND 22 EXCEPT FOR A REDUCED CLAD THICKNESS OF 0.20 INCH. TEST PLATE WAS SUPPORTED WITH 0.250 INCH ALUMINUM BACKUP PLATE.

Based on prior experience at MTL with the ballistic performance of the Al_2O_3 ceramic plates (supplied by MTL), the ballistic performance of the reduced density 6061 Al clad plates was disappointing. The ballistic test results were comparable to unclad Al_2O_3 test results indicating almost no contribution of the aluminum alloy cladding to the ballistic performance. This was attributed to the lower than typical density of the cladding material that resulted from the lower pressing pressure (25,000 psi vs. 55,000 psi) used in applying the cladding.

Despite the higher density aluminum cladding of the HIPed plates, no measurable improvement in ballistic performance was obtained. Both of the HIPed plates were tested with an 0.250 inch aluminum backup support plate. These tests resulted in partial penetration with the damage to the cladding material limited to a small amount of backside bulging and some cracking of the back-face cladding.

The ballistic performance of the Group III (Table V) armor designs against a .50 caliber APM2 threat were similar to those described above for .30 caliber APM2 tests.

Comparison of these armor systems to conventional ceramic and aluminum composite armor systems shows that these armor systems are not particularly weight efficient. Target Groups I and II are 35-40% less effective than comparable ceramic/aluminum armor systems. Target Group #3 is 32% less effective than comparable ceramic/aluminum armor systems versus the .50 cal APM2 threat. It can be concluded that these armor systems cannot compete with other armor systems on a weight basis.

The principle reason for the low efficiency of these systems is the sacrificial weight of cladding which provides little if any support to the ceramic. While the added weight of cladding provides little if any improvement in ballistic performance, it does add to the overall weight of the armor system.

6061 Al Clad Metalized Ceramic Armor Designs vs. .50-Caliber APM2 Threat

This series of tests evaluated the use of metallization layers to improve the bonding between ceramic and cladding, the effect of increased cladding strength by hot isostatic pressing (HIP) and a new armor material system using SiC ceramic clad with 6061 Aluminum. The SiC/6061 Al clad system was evaluated because the compatibility of these materials had been demonstrated by recent metal matrix composite fabrication studies conducted independently by Dynamet Technology. Although HIPing and metallization layers were attempted in the earlier test series, it was felt that these new metallization layers and hot isostatic pressing would significantly improve the strength and ductility of the cladding. Table VII describes the armor system designs fabricated and the target plates are shown in Figure 24.



Figure 24. 6061 Al CLAD TARGET PLATES INCORPORATING SiC AND Al₂O₃ CERAMIC TILES. CERAMIC TILES WERE METALLIZED TO PROMOTE BONDING TO 6061 Al CLADDING AND CLAD PLATES WERE HIPed.

Table VII

6061 Al CLAD CERAMIC DESIGNS FABRICATED WITH METALLIZED CERAMICS AND HIPED CLADDING

Group	Ceramic/ Thickness	Clad Thickness	Metallization	Total Thickness	Areal Density (psf)
I	0.500 inch/SiC	3/16 inch/side	Ag	7/8 inch	13.3
II	0.700 inch/Al ₂ O ₃	0.21 inch/side	Mo-Mn	1 1/8 inch	18.5
III	0.700 inch/Al ₂ O ₃	0.21 inch/side	Mo-Mn-Ni	1 1/8 inch	18.5

To conserve ceramic material, the nominal dimensions of the tiles were 4 inches x 4 inches instead of 6 inch x 6 inch plates used in earlier designs. The thicknesses of the SiC and Al₂O₃ plates were 0.500-inch and 0.700-inch, respectively.

The SiC tiles had an approximate 0.001 inch thick silver (Ag) layer applied to all surfaces. One group of Al₂O₃ tiles had a 0.001 inch layer of Mo-Mn applied to all surfaces while the second group of Al₂O₃ tiles was metallized with Mo-Mn-Ni having a total thickness of about 0.003 inch.

Following metallization the ceramics were clad with 6061 Al by low pressure isopressing (25,000 psi) and sintering, and the clad plates were HIPed. Cladding thicknesses were about 0.20 inch on the front and back faces and 0.30 inch along the edges. Overall dimensions measured 4 5/8 inch x 4 5/8 inch with a total thickness of 7/8-inch for the SiC targets and 1 1/4-inches for the Al₂O₃ targets.

These designs were tested against a .50 caliber APM2 threat with results summarized in Table VIII. In all cases the aluminum cladding material was severely cracked and broken into several small pieces. With the limited support provided by the cladding material, the encapsulated ceramic tiles were not well contained and this resulted in severe damage to the tiles. The threat velocities ranged from a low of 2795 ft/sec to a high of 3238 ft/sec.

The threat velocities for complete penetration of the Al₂O₃ target designs (Groups II and III) are similar while for the SiC design it is about 200 ft/sec slower. These results indicate that the different metallization layers do not affect ballistic performance significantly, which is consistent with what was observed in other ballistic tests. The results illustrate the superior ballistic performance of SiC which although significantly thinner than the Al₂O₃ tiles, performed nearly as well.

The ballistic performance of these targets correlated well with the armor designs tested previously. It is apparent that the HIPing does not significantly improve the ballistic performance or the potential multiple-hit capability nor does the addition of bonding aides improve performance significantly. In addition, it seems the strength and ductility of the cladding could be improved.

The SiC ceramic clad with 6061 Aluminum performed comparably with the TiB₂/Ti and Al₂O₃/6061 Al systems tested previously.

Table VIII.

SUMMARY OF 6061 AL HIP CLAD METALIZED SIC AND Al_2O_3 TARGETS TESTED AGAINST .50-CALIBER APM2 THREATS

Target Group	No.	Ceramic	Test No.	Shot No.	7039 Aluminum		Velocity (ft/sec)	Result
					Backup Added	Total Areal Density (psf)		
I	1	SIC	88-516	1	0.250 inch	16.8	2969*	Complete Penetration
	2	SIC		2	0.250 inch	16.8	xxxx*	*
	3	SIC		3	0.250 inch	16.8	xxxx*	*
	4	SIC		4	0.250 inch	16.8	xxxx*	
II	1	Al_2O_3	88-516	1	0.500 inch	25.5	xxxx*	*
	2	Al_2O_3		2	0.500 inch	25.5	xxxx*	Partial Penetration
	3	Al_2O_3		3	0.500 inch	25.5	xxxx*	Partial Penetration
	4	Al_2O_3		4	0.500 inch	25.5	xxxx*	Partial Penetration
III	1	Al_2O_3	88-514	1	0.500 inch	25.5	xxxx*	*
	2	Al_2O_3		2	0.500 inch	25.5	xxxx*	*
	3	Al_2O_3		3	0.500 inch	25.5	xxxx*	*
	4	Al_2O_3		4	0.500 inch	25.5	$V_{50}=xxxx^*$	*

*CLASSIFIED

Multi-Tile Armor Designs

As a means of obtaining multi-hit armor plates, multiple tile targets based on both TiB_2 and Al_2O_3 ceramics were fabricated and tested. The multi-tile armor designs and the ballistic test results are described in the following section and summarized in Table IX and X, respectively.

Four Tile Al_2O_3 /6061 Al Clad Target

This initial multi-tile ceramic armor design incorporated four (4) ceramic tiles each 3 inches x 3 inches x 0.75 inch thick separated by about 1/4 inch of 6061 Al clad material and clad on front and back faces with a 1/2 inch thickness of 6061 Al. Overall dimensions were 6 3/4 inches x 6 3/4 inches x 1 3/4 inch thick.

This prototype plate was ballistically tested against two .50-caliber APM2 threats at strike velocities of about 2500 ft/sec. The front face of the multi-cell plate and the external damage resulting from the two shots is shown in Figure 25.



Figure 25. FOUR TILE Al_2O_3 /6061 Al CLAD ARMOR DESIGN BALLISTICALLY TESTED AGAINST two .50-CALIBER APM2 THREATS. OVERALL DIMENSIONS WERE 6 3/4 X 6 3/4 X 1 3/4 INCHES THICK.

The first shot which was fired at the lower left corner tile, resulted in substantial damage to the surrounding clad material. The clad on the perimeter was totally removed and a moderate bulge formed on the back side with some associated cracking. The ceramic tile was broken down into small fragments in which the majority exited through the large hole generated by the impact.

The second shot was fired at the tile diagonally across from the first tile and resulted in considerably less damage to both the surrounding cladding material and to the tile itself. The bulge on the back side protruded approximately 1/2 inch with some cracking present. The cladding material remained intact on the perimeter, resulting in total containment of the ceramic tile.

To determine the damage sustained by the two remaining ceramic tiles and the overall condition of the armor plate, the multi-cell plate was radiographed. The damage revealed in the x-ray is shown in the sketch of Figure 26 and photograph Figure 26A. Some cracking was present in both of the untested tiles, but overall the tiles remained in position and were isolated from the shock generated by the ballistic testing. It appears that a .50 caliber AP round could be fired into each of the remaining intact tiles without any more severe damage occurring than did on the previous two test shots.

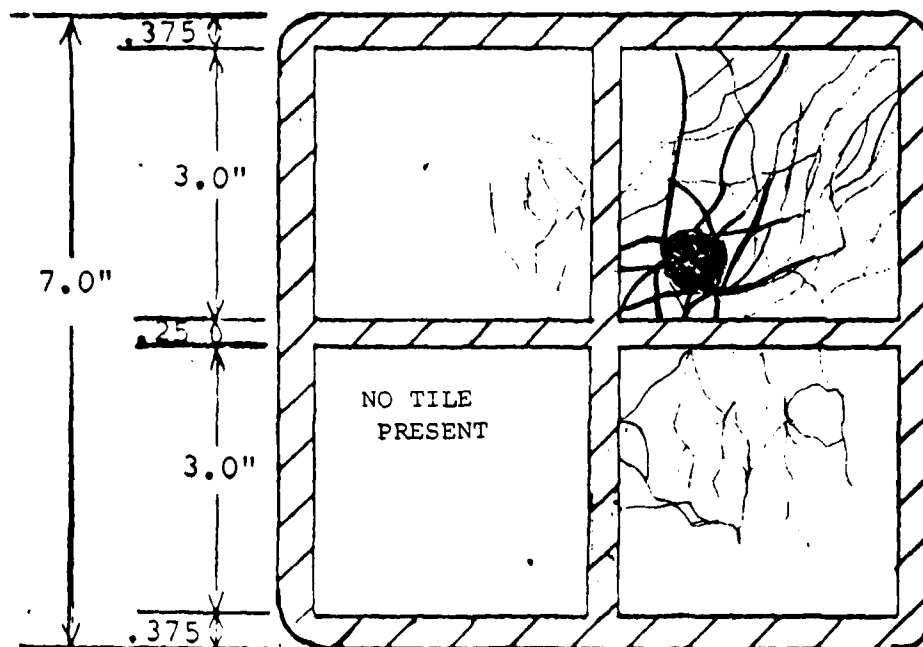


Figure 26. SKETCH OF RADIOGRAPH SHOWING INTERNAL DAMAGE OF ENCAPSULATED Al_2O_3 TILES OF MULTI-TILE TARGET.



Ductile Alloy Encapsulated Multi-cell Ceramic Armor

Figure 26A. PHOTOGRAPH FROM RADIOGRAPH SHOWING INTERNAL DAMAGE OF ENCAPSULATED Al_2O_3 TILE OF MULTI-TILE TARGET (IMAGE REVERSED).

Table IX.

MULTI-TILE ARMOR DESIGNS INCORPORATING Al_2O_3 AND TiB_2 CERAMIC TILES

Armor Design	Multi-Tile Array	Cladding	Areal Dimension (inches)	Total Thickness (inch)	Aerial Density (psf)
1	4-Tile Al_2O_3 3inch x 3inch x .75inch	6061 Al 1/2inch/side	6 3/4x 6 3/4		30.1
2	8-Tile Al_2O_3 3inch x 3inch x .75inch	6061 Al 1/4inch/side	6 3/4x 14 3/4	1 1/4	19
3	2-Tile TiB_2 6inch x 6inch x 0.5inch	Ti-6Al-4V 1/8 inch/side	6 3/4 x 14 3/4	7/8	20
4	4-Tile TiB_2 3inch x 3inch x 0.5inch	Ti-6Al-4V 1/4inch/side	6 x 6	1	27

Table X.

SUMMARY OF BALLISTIC TESTING OF MULTI-TILE ARMOR DESIGNS VS. .50 CALIBER APM2 THREATS

Armor Design	Test No.	Shot No.	Backup Added	Areal Density (psf)	Impact Velocity	Observations
1	88-829	1	0.250 inch	33.6	2620	Partial Penetration
		2	0.250 inch	33.6	2635	Partial Penetration
2	89-143	1	0.50 inch	26	2xxx*	Partial Penetration
		2	0.50 inch	26	2xxx*	target broke in half Partial Penetration
3	89-142	1	0.50 inch	27	2xxx*	Partial Penetration, small bulge in backup
		2	0.50 inch	27	2xxx*	Partial Penetration, cladding fractured
4	89-347	1	0.50 inch	34	2491	Partial Penetration
		2	0.50 inch	34	2742	Partial Penetration

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Eight Tile Al₂O₃ Ceramic/6061 Al Cladding

This multi-tile armor design consisted of eight Al₂O₃ ceramic tiles clad with and separated by 6061 Al. Each tile measured 3 inches x 3 inches x 0.750 inch thick with overall plate dimensions of 14 3/4 inches x 6 3/4 inches x 1 inch thick. Clad thickness was about 1/8 inch on each face. This plate was manufactured by cold isostatic pressing followed by vacuum sintering using processing parameters similar to what has already been reported for other experimental 6061 Al clad armor plates. Final density was about 95% of full density. This plate is shown in Figure 27.

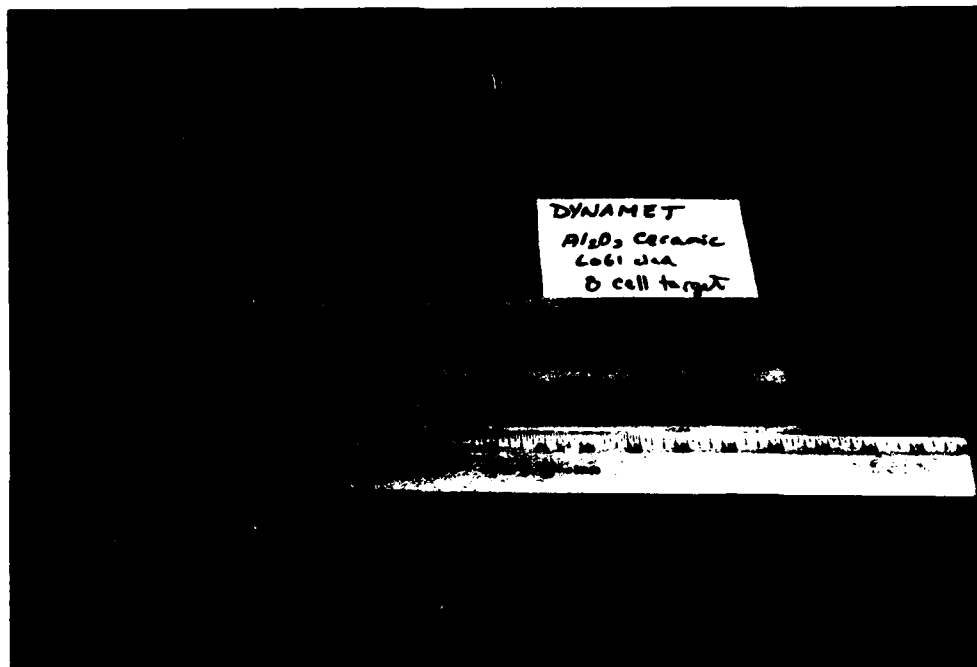


Figure 27. EXPERIMENTAL ARMOR PLATE DESIGN CONSISTING OF AN ARRAY OF EIGHT Al₂O₃ CERAMIC TILES CLAD WITH 6061 Al.

This armor design was tested against two .50 caliber APM2 threats fired into two locations. The target was backed by a 0.500 inch 7039 Al alloy plate.

The first shot was fired at the second tile from the right in the top layer. The threat velocity was 2XXX ft/sec and resulted in partial penetration of the plate. After impact the plate cracked into two half-sections of four tiles each. A second shot was fired at a similar velocity (2XXX ft/sec) at a corner tile of the remaining half-section, resulting in another partial penetration of the target. As with the first shot, severe cracking occurred in the surrounding clad, but the damage to the adjacent Al₂O₃ tiles was limited.

These results suggest that by increasing the thickness of the clad layer on the front face and, on the back face the severe damage to the clad layers could be lessened and the multi-hit capabilities of this armor system enhanced. Such improvement was demonstrated with the 4-tile Al_2O_3 /6061 Al target, in addition to the two tile TiB_2 /Ti-6Al-4V design described below.

Two Tile TiB_2 Ceramic/Ti-6Al-4V Alloy Cladding

This multi-tile array consisted of two TiB_2 plates 6 inches x 6 inches x 0.500 inch thick clad with and separated by a layer of Ti-6Al-4V alloy. Overall plate dimensions were 14 3/4 inches x 6 3/4 inches x 7/8 inch with a clad thickness of about 1/8 inch on each side. This plate which is shown in Figure 28, was fabricated by standard pressing and vacuum sintering.

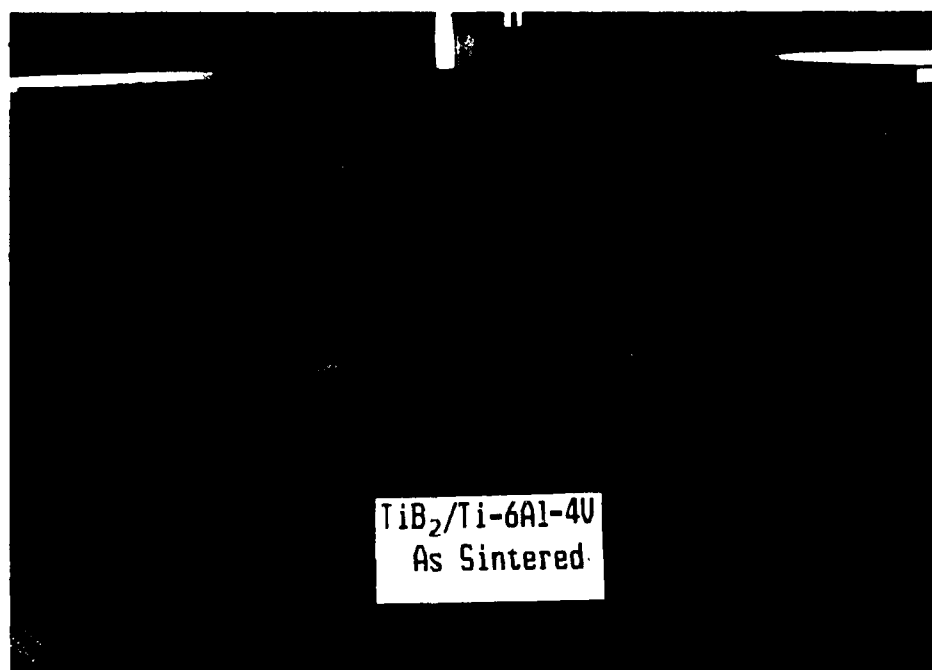


Figure 28. TWO-TILE TiB_2 ARMOR DESIGN WITH Ti-6Al-4V CLADDING

This armor design was tested against two .50 caliber APM2 threats, one fired into each tile. The target plate was backed with a 0.500 inch 7039 Al plate.

The first shot was fired at a velocity of 2XXX ft/sec into the left TiB_2 tile and resulted in major front and back face cracking, minor damage to the right side clad and unknown damage to the right side TiB_2 tile. The second shot was fired at the right side tile (2XXX ft/sec) resulting in severe clad and tile damage.

Four Tile TiB₂ Ceramic/Ti-6Al-4V Alloy Cladding

This multi-tile ceramic array consisted of four tiles of TiB₂ clad with Ti-6Al-4V. Overall dimensions were about 6 3/4 inches x 6 3/4 inches x 1 inch thick. Tile thickness was 0.500-inch rather than the 0.750 inch thickness used in the two-tile TiB₂ design, allowing for a thicker clad thickness of 1/4-inch on both faces.

This target exhibited multi-hit capability. Two shots were defeated with only partial penetration of the armor. More important the damage to the individual ceramic tiles was isolated to the cell or tile directly hit. However, due to a bow in the armor plate the second impact created a moment on the cladding material between the ceramic tiles causing the multi-cell armor system to fracture in half. This made it impossible to impact the armor system with a third shot.

Clad Microcomposite (CM³C) Armor

An initial evaluation of the CM³C type armor plate involved two microcomposite-cladding combinations; one composed of SiC-6061 Al microcomposite encapsulated with 6061 Al and a second type comprised of a TiB₂/Ti-6Al-4V microcomposite clad with Ti-6Al-4V alloy. Figures 29 and 30 illustrate the configuration and designs for these particular CM³C plates. The details of the designs are summarized in Table XI and the ballistic testing in Table XII.

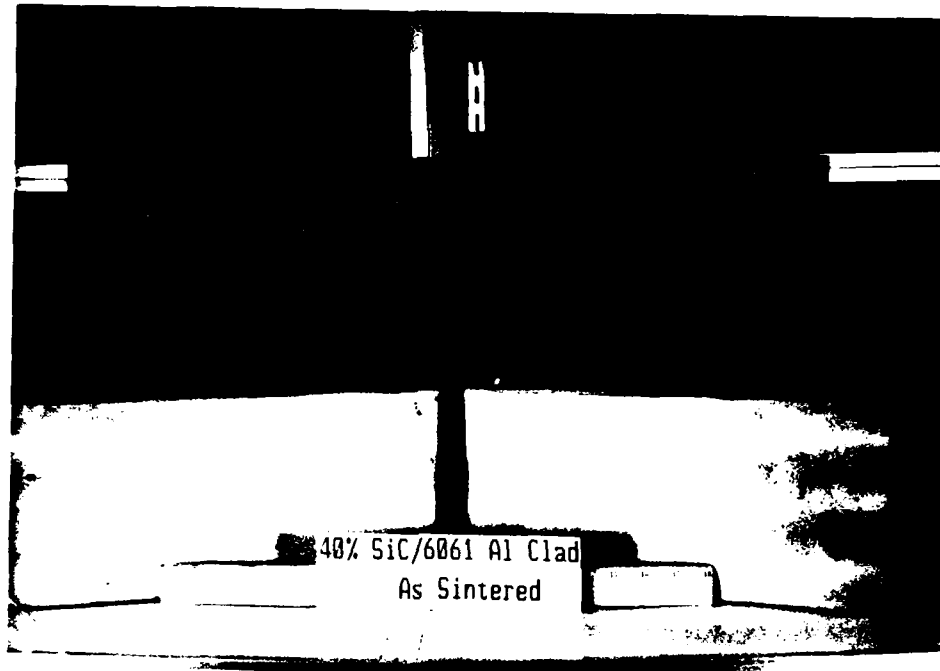


Figure 29. CM³C ARMOR DESIGNS WITH 40% SiC/6061 Al MICROCOMPOSITE CORE CLAD WITH 6061 Al.

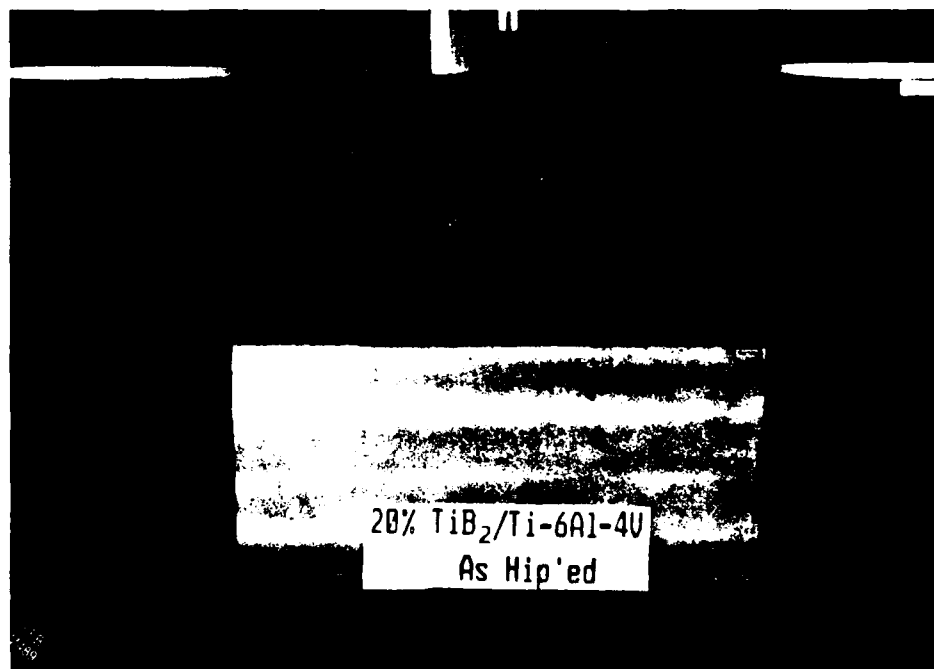


Figure 30. CM³C ARMOR DESIGN WITH 20% TiB₂/Ti-6Al-4V MICROCOMPOSITE CORE CLAD WITH Ti-6Al-4V.

40% SiC/6061 Al Microcomposite with 6061 Al Cladding - CM³C #1, #2 and #3

Three armor designs based on this microcomposite/clad combination were fabricated, as shown in Table XI. These three armor designs were tested against 0.50 AP M2 threats. The first plate with a total thickness of 1 1/2 inches was fired at a total of three times with threat velocities of 2160, 1614, 1192 ft/sec, respectively, and without any back-up support. All three shots resulted in complete penetrations, indicating little resistance to the threat.

The second plate with 1 inch thickness was shot at four times at threat velocities of 2222, 2019, 1514, 1477 ft/sec, respectively, while being backed with a 0.500-inch 7039 Al plate. Similar to the results obtained with the first plate, the first two shots penetrated the plate and the back-up plate with little resistance. The last two shots were fired at lower velocities and both resulted in partial penetrations.

The third plate using the SiC/6061 Al CM³C microcomposite was in the same design configuration as CM³C #2 with the addition of the HIP processing step.

25% SiC/6061 Al Microcomposite with 6061 Al Cladding - CM³C #4

This plate consisted of a 25% SiC microcomposite core and a 6061 Al cladding. Nominal plate dimensions and thickness of cladding were about the same as plates #1 and #2.

20% TiB₂/Ti-6Al-4V Microcomposites with Ti-6Al-4V Cladding

CM³C #5. A CM³C plate design consisting of a 20% TiB₂/Ti-6Al-4V microcomposite core and a surrounding cladding of Ti-6Al-4V (Figure 30). Overall plate dimensions were 14 3/4 inch x 6 3/4 inch x 1 inch thick with a clad thickness of about 1/8 inch thick on each side. This plate was HIPed, after cold pressing and vacuum sintering to obtain a fully dense cladding and a 95% dense microcomposite core.

This HIP'ed plate was tested against two 0.50 caliber AP M2 threats fired into two locations. The armor plate was backed for the second shot as in plates #1 and #2 but was without a back-up plate for the first shot.

The first shot (1343 ft/sec) was fired at the center of the plate and resulted in complete penetration. A large section (3" diameter hole) of the composite and back face was blown out by the impact. The areas around the impact zone appeared to be unaffected with no evidence of backside cracking of the cladding.

The second shot (998 ft/sec) was fired to the right of shot #1. This time the plate was backed with 0.500-inch 7039 Al plate. This shot resulted in a very slight bulge on the back surface and minor cracking on the back face clad. Because this test result was encouraging, a second plate of this design which incorporated the added support of the back-up plate as part of the armor design was fabricated and tested, as follows.

CM³C #6. This plate consisted of a 20% TiB₂/Ti-6Al-4V microcomposite core and a surrounding clad of Ti-6Al-4V. Nominal design dimensions were 14 inches x 7 inches x 1 inch thick with a clad thickness of about 1/16 inch on the front face and 3/8 inch on the back face.

The CM³C targets behaved much like ceramic armors when impacted by the .50 caliber AP M2 projectile. Due to the low ductility of the composites, tensile failure at the rear surface resulted in excessive spall and rear plate blow out.

From these ballistic tests the CM³C material systems fabricated under this program do not show adequate performance as armor materials. The SiC/6061 Al composite targets performed 10% inferior to typical wrought aluminum armor alloys and the TiB₂/Ti-6Al-4V composite performed 32% inferior to wrought Ti-6Al-4V armor for the same threat levels.

An interesting observation was made during the CM³C ballistic testing. The 25% SiC reinforced CM³C fractured more severely than the composite with 40% SiC particulate reinforcement. On further consideration it was concluded that the lower density in the 40% SiC reinforced CM³C resisted crack propagation therefore improving the structural integrity of the armor system but also resulted in a lower ballistic limit. There are several parameters in the processing of the CM³C materials which could be optimized for ballistic performance. The increased strength and hardness of these materials warrant further ballistic investigation but the low ductility and low theoretical density must be improved if these materials are to demonstrate useful ballistic properties.

Table XI.

CM³C ARMOR DESIGNS INCORPORATING SiC/6061 Al AND TiB₂/Ti-6Al-4V MICROCOMPOSITES

Armor Design	Microcomposite Core	Cladding	Fabrication Process	Areal Dimensions (inches)	Total thickness (inches)	Areal Density (psf)
1	40%SiC/6061 Al 3/4 inch thick	6061 Al 1/8 inch/side	CIP/Sinter	6 3/4 x 14 3/4	1	15
2	40%SiC/6061 Al 1/2 inch thick	6061 Al 1/2 inch/side	CIP/Sinter	6 3/4 x 14 3/4	1 1/2	23
3	40%SiC/6061 Al 1/2 inch thick	6061 Al 1/4 inch/side	CHIP	6 x 12	1	14
4	25%SiC/6061 Al 1/2 inch thick	6061 Al 1/16 inch front 3/16 inch back	CHIP	6 x 12	1	14
5	20% TiB ₂ /Ti-6Al-4V 3/4 inch thick	Ti-6Al-4V 1/16 inch/side	CHIP	6 3/4 x 14 3/4	7/8	23
6	20% TiB ₂ /Ti-6Al-4V 3/4 inch thick	Ti-6Al-4V 1/8 inch front 3/8 inch back	CHIP	6 x 12	1 1/4	31

Table XII.

SUMMARY OF BALLISTIC TESTING OF CM³C ARMOR DESIGNS VS. .50 CALIBER APM2 THREATS

Armor Design	Test No.	Shot No.	7039 Aluminum Backup Added	Total Areal Density (psf)	Impact Velocity (ft/sec)	Observations
1	89-144	1	0.50 inch	22	2272	Complete Penetration
		2	0.50 inch	22	2019	Complete Penetration
		3	0.50 inch	22	1514	Partial penetration, void projectile yaw
		4	0.50 inch	22	1417	Partial penetration, void projectile yaw
2	89-140	1	None	23	2160	Complete Penetration
		2	None	23	1614	1-1 1/2" exit hole
		3	None	23	1192	Complete Penetration, no cracking
3	89-345	3&5	0.50 inch	21	V ₅₀ =1650	Minor Cracking
4	89-344	3&4	0.50 inch	21	V ₅₀ =1792	Minor cracking
5	89-141	1	None	23	1343	Complete Penetration, large exit hole
		2	0.5 inch	30	998	Partial Penetration, Medium Rear bulge
6	89-346	2&4	0.5 inch	38	V ₅₀ =2158	Minor Cracks

CONCLUSIONS

This SBIR Phase II program has led to the development of a complete fabrication process for the encapsulation or cladding of ballistic resistant ceramic armor elements with light weight, ductile metals and alloys. Specific conclusions and achievements of the process development studies include the following:

1. A wide variety of clad ceramic armor designs can be fabricated using low cost, re-usable tooling. The potential armor design variations range from small single-tile plates to large multi-tile cellular panels with specified variations in the cladding thickness from face-to-face, side-to-side and within the walls separating neighboring tiles of cellular designs.
2. By a combination of pre-processing of the ceramic tiles and optimized method of sintering and hot isostatic pressing nearly fully dense metal cladding and ceramic-to-metal bonding has been achieved in full size armor plates without degrading the ballistic performance of the ceramic materials.
3. The fabrication process and metal/ceramic bonding has been successfully applied to the following monolithic ceramic/metal armor systems:
 - a. TiB_2 /Titanium (Commercial Purity and Ti-6Al-4V alloy)
 - b. Al_2O_3 /6061 Aluminum Alloy
 - c. SiC/6061 Aluminum Alloy

Successful metal cladding was also achieved with the combination of Al_2O_3 /Titanium but less efficient ballistic performance ruled out further development of this clad armor system.

4. In addition to cladding monolithic ceramic tiles the process has been successfully applied to the cladding of particle reinforced metal matrix composites incorporating particulate TiB_2 and SiC in matrices of Ti-6Al-4V and 6061 aluminum, respectively. The successful fabrication process illustrates the flexibility of the Dynamet cladding technology and its potential with current ballistic resistant ceramics as well as for cladding the toughened ceramics now being developed.

A variety of prototype metal-clad ceramic armor designs were fabricated and tested against caliber .30 and caliber .50 APM2 projectiles. The ballistic performance testing led to the following conclusions:

1. Multi-hit capability was demonstrated with the titanium alloy (Ti-6Al-4V) clad TiB_2 ceramic armor and with the aluminum alloy (6061) clad Al_2O_3 ceramic armor. This was particularly evident when the ceramic was incorporated as individual tiles and clad with the ductile metal alloy. Although a specific tile was destroyed upon impact the remainder of the configuration remained intact to offer continued ballistic protection.

Although the total ballistic limit of the composite plates were somewhat lower than ceramic armor because of the added weight of the softer metal alloy clad, the advantage of repeat hit capability offsets a slightly lower ballistic limit. Another advantage of these armor designs is their ease of integration with metallic armored fighting vehicles or other metal structures as required for specific applications.

2. The initial feasibility of utilizing an inexpensive microcomposite of TiB_2 and Ti-6Al-4V powder and of SiC and Al-6061 consolidated powders indicated that this low cost procedure (avoiding expensive monolithic ceramic fabrication) is feasible. The ballistic properties were low because of the low density and plate curvature of these initially manufactured plates. Higher density and good flatness would be achieved by introducing a forging operation to the process (see recommendations), with the potential for improving ballistic performance to an acceptable level.

RECOMMENDATIONS

Based on the experimental results achieved it is recommended that additional plates be manufactured for ballistic testing as follows:

1. Multi-tile plates 6 inch x 12 inch with TiB_2 tiles enclosed with Ti-6Al-4V. These plates might employ smaller tiles and the manufacturing procedure modified to attain better flatness (to mesh better against the backplate).
2. Microcomposite plates should be manufactured with higher density and better flatness than those initially fabricated. This would be accomplished by adding the forging step subsequent to the CHIP process to densify the components from 90-95% of theoretical density to 100% dense.

The composite compositions to be manufactured by this process would include 20% TiB_2 /Ti-6Al-4V and 25% SiC/6061 Al as well as 40% SiC/6061 Al. These would be clad with Ti-6Al-4V alloy and 6061 Al alloy respectively.

The 20% TiB_2 /Ti-6Al-4V composite manufactured by the CHIP process followed by extrusion to full density has achieved 180,000 psi ultimate strength with 1% elongation. These properties indicate the potential for improved ballistic performance when a further densification step is added to the manufacturing process.

3. It is recommended that scale-up of this developmental effort be undertaken with specific component application and specific protection mission as objectives.
4. It is recommended that this technology of encapsulating ceramic tiles in a ductile matrix, as well as manufacture of microcomposites and CM^3C structure be disseminated to other DOD areas so that appropriate applications can be identified where further development of this general technology could accomplish specific program objectives.

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